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On the time-course of adjacent and non-adjacent transposed-letter priming

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Abstract

We compared effects of adjacent (e.g., atricle-ARTICLE) and non-adjacent (e.g., actirle-ARTICLE) transposed-letter (TL) primes in an ERP study using the sandwich priming technique. TL priming was measured relative to the standard double-substitution condition. We found significantly stronger priming effects for adjacent transpositions than non-adjacent transpositions (with 2 intervening letters) in behavioral responses (lexical decision latencies), and the adjacent priming effects emerged earlier in the ERP signal, at around 200 ms post-target onset. Non-adjacent priming effects emerged about 50 ms later and were short-lived, being significant only in the 250-300 ms time-window. Adjacent transpositions on the other hand continued to produce priming in the N400 time-window (300-500 ms post-target onset). This qualitatively different pattern of priming effects for adjacent and non-adjacent transpositions is discussed in the light of different accounts of letter transposition effects, and the utility of drawing a distinction between positional flexibility and positional noise.

Keywords

transposed-letter effects; sandwich priming; ERPs; letter position coding; non-adjacent letters

There is a long history of research attesting to the fact that letter strings that differ by transposing two letters are perceptually more similar than letter strings that differ by changing two letters (see Duñabeitia, Dimitropoulou, Grainger, Hernández, & Carreiras, 2012; and Massol, Duñabeitia, Carreiras, & Grainger, 2013, for two recent studies). For example, more errors are made to real word anagrams as well as nonword anagrams formed by a single transposition (e.g., trial-trail, jugde-judge) compared with non-anagram controls (Andrews, 1996; Bruner & O'Dowd, 1958; Chambers, 1979; O'Connor & Forster, 1981; Perea, Rosa, & Gómez, 2005). Although such letter transpositions do hinder reading for meaning compared with unaltered text, reading behavior is still remarkably fluent, and

particularly when the transpositions involve inner-letters (Rayner, White, Johnson, & Liversedge, 2006).

When used as prime stimuli in the masked priming paradigm (Forster & Davis, 1984), transposed-letter (TL) primes facilitate target word recognition compared with appropriate control primes (e.g., jugde-JUDGE vs. jupte-JUDGE, caniso-CASINO vs. caviro-CANISO: Perea & Carreiras, 2006; Perea & Lupker, 2003, 2004; Schoonbaert & Grainger, 2004). Analogous phonological transpositions fail to produce any priming effects (Perea & Carreiras, 2006), and TL priming appears to be impervious to context-dependent changes in pronunciation (Perea & Carreiras, 2008). Therefore, TL priming is believed to arise mainly from an orthographic level of processing driven by a mechanism that maps position-coded letter identities onto whole-word orthographic representations (Grainger, 2008).

Perhaps the simplest explanation of TL effects is that they reflect the influence of noise operating on an otherwise precise mechanism for encoding letter position information (e.g., Norris, 2006; Norris, Kinoshita, & van Casteren, 2010; Gómez, Ratcliff, & Perea, 2008).¹ Under this view, TL effects are not the result of the mechanism used to encode letter position information, but rather the result of noise operating on a system that would otherwise not show TL effects. Such positional noise is thought to be generic, that is, it operates on strings of letters just like sequences of other kinds of familiar visual objects (Garcia-Orza, Perea, & Muñoz, 2010). However, TL effects might also be caused by flexibility in the very mechanism that is used to code for letter position information. One specific letter-position coding scheme, called open-bigram coding, is characterized by such flexibility, and accounts for TL effects without appealing to positional noise (Grainger & van Heuven, 2003; Grainger & Whitney, 2004; Hannagan & Grainger, 2012; Whitney, 2001). In other words, it is the mechanism used to code for the order of letters in a word (word-centered letter positions) that generates the positional flexibility that can account for TL effects, without having to introduce positional noise.

Here we propose that both positional noise and positional flexibility are sources of TL priming effects. For illustrative purposes, the influence of these two factors is described within one particular framework for orthographic processing, but the key point here is the need to distinguish between these two mechanisms. The theoretical framework is Grainger and Ziegler's (2011) model of orthographic processing that builds on the earlier work of Grainger and van Heuven (2003). In the model, shown in Figure 1, processing flows from location-specific letter representations to location-invariant sublexical orthographic representations that consist of letters and letter combinations, and from there to whole-word orthographic representations. Location-specific letter representations indicate that a given letter identity is present in the stimulus at a particular location relative to eye fixation, but do not inform about the position of letters in the stimulus. This information is carried by location-invariant sublexical representations in two different ways: by coding for ordered combinations of contiguous and non-contiguous letter sequences (open-bigrams), and by coding for precise position-in-string information using space-letter and letter-space

¹Note that the term "position" here refers to within-word letter position, independently of the location of the word with respect to eye fixation.

combinations (akin to the both edges coding scheme of Fischer-Baum, McCloskey & Rapp, 2010; Fischer-Baum, Charny, & McCloskey, 2011; see Hannagan & Grainger, 2012, for more details). The first scheme provides positional flexibility (referred to as coarse-grained orthography by Grainger and Ziegler, 2011), while the second provides positional precision in the same way as location-specific letter representations, except that positional information is now stimulus-centered rather than gaze-centered. Grainger and Ziegler (2011) referred to these precise stimulus-centered representations as the fine-grained orthographic code. TL effects naturally fall-out of the flexible coding scheme, whereas they are the result of noise in the precise position coding representations. Therefore, in this model there are three distinct sources of TL effects: 1) positional noise operating on location-specific letter detectors; 2) flexible coarse-grained orthographic representations; and 3) positional noise operating on positionally precise fine-grained orthographic representations.

The present study provides a further exploration of this theoretical framework by testing for adjacent and non-adjacent TL priming effects with ERP recordings. The adjacent vs. non-adjacent TL manipulation is designed to index the relative influence of positional flexibility and positional noise in driving TL priming effects. Adjacent TL primes should systematically generate stronger priming effects than non-adjacent TL primes, since by all accounts of letter-position coding the orthographic overlap is greater in the former. Prior behavioral research has indeed shown that adjacent TL priming is greater than non-adjacent TL priming (Perea, Duñabeitia, & Carreiras, 2008; see Lee & Taft, 2009, for a similar finding with unprimed lexical decision). However, the time-course of the difference in the size of adjacent and non-adjacent ERP priming effects, will inform us as to changes in the relative contribution of positional flexibility, with a greater role for this mechanism causing a reduction in the difference between the two types of priming. That is, when positionally precise orthographic representations dominate processing, as is the case when processing is centered on location-specific letter representations (see Figure 1), then we expect to see much larger adjacent TL priming than non-adjacent TL priming. However, when coarse-grained flexible orthographic representations dominate processing, then we expect to see a reduced advantage for adjacent TL priming over non-adjacent TL priming.

Our experiment is also motivated by prior research investigating ERP priming effects from subset primes (Carreiras, Duñabeitia, & Molinaro, 2009; Grainger & Holcomb, 2009a; Ktori, Grainger, Dufau, & Holcomb, 2012). These studies found evidence that the early part of the N250 ERP component (200 – 250 ms post-target onset) reflects the mapping of location-specific abstract (shape and case-invariant) letter representations onto location-invariant sublexical orthographic representations. The later part of the N250 (250 – 300 ms post-target onset) would, on the other hand, reflect the mapping of location-invariant sublexical orthographic representations onto whole-word representations. These studies found significant priming for hyphenated subset primes (e.g., prime “c-lle-t” for the target “collect”) starting at around 200 ms post-target onset, whereas priming effects for concatenated subset primes (e.g., cllet-collect) only started to emerge at around 250 ms post-target onset. Moreover, the earlier hyphenated priming effect was cancelled by displacing prime stimuli horizontally with respect to target stimuli, whereas the concatenated priming effect was not affected by prime displacement (Ktori et al., 2012). This clearly points to location-specific letter representations as the source of the early hyphenated priming effect,

and to location-invariant orthographic representations as the source of the later concatenated priming effect. We therefore predict that only adjacent TL effects should be seen in the early N250 time-window, whereas both adjacent and non-adjacent TL effects should be present in the late N250 time-window. Effects of both adjacent and non-adjacent TL primes should also be seen on the N400 component, thought to reflect the mapping from whole-word orthographic representations onto semantics (see Grainger & Holcomb, 2009b, for a summary of ERP masked priming effects).

Following Ktori et al. (2012), in the present study we use a variant of masked priming called sandwich priming (Lupker & Davis, 2009) since it has been shown to provide stronger measures of priming. Seven-letter targets were primed by adjacent TL primes (e.g., atricle-ARTICLE) and their double-substitution controls (e.g., aqnicle-ARTICLE) as well as non-adjacent (with two intervening letters) TL primes (e.g., actirle-ARTICLE) and the corresponding double-substitution controls (e.g., aqtinle-ARTICLE). ERPs were recorded in order to track the time-course of adjacent and non-adjacent TL priming effects.

Method

Participants

Twenty-four volunteers, drawn from the undergraduate and postgraduate population of Aix-Marseille University, were paid to take part in the experiment. The data of four participants were excluded from analysis because of excessive eye movement artifact. The remaining twenty participants (13 female, 7 male) ranged in age from 19 to 28 years (mean 22, sd 2.54). All participants were right-handed native speakers of French and reported having normal or corrected-to-normal vision, and none reported any linguistic or neurological impairment.

Design and Stimuli

All stimuli used were 7-letters long and bore no diacritics. A set of 192 words was selected from the French lexical database Lexique (New, Pallier, Brysbaert, & Ferrand, 2004). Word stimuli were nouns or adjectives in infinitive form and their printed frequency ranged between 5 and 380 occurrences per million with a mean of 33. An additional set of 192 nonwords was selected from the French Lexicon Project (Ferrand, New, Brysbaert, Keuleers, Bonin, Méot, Augustinova, & Pallier, 2010) for the purpose of the lexical decision task. In order to ensure the effectiveness of the selected stimuli, mean response accuracy collected from a lexical decision task as part of the French Lexicon Project was taken into consideration and was no less than 99%. Furthermore, the CVC orthographic structure of the nonword stimuli had the same distribution as with the word stimuli. These target stimuli (i.e., words and nonwords) were paired with an equal number of TL and substitution primes. TL primes were formed by transposing two letters of a given stimulus, and substitution primes were formed by substituting two letters not present in the stimulus. Care was taken so that a change, be it transposition or substitution, always involved at least one consonant letter while none of the changes involved letter repetition. Substituted letters were matched to transposed letters in terms of consonant-vowel status, but not for visual similarity. The distance in letter positions along the stimulus string varied so that the change (i.e.

transposition or substitution) involved adjacent letter positions (i.e., Positions 2-3, 3-4, 4-5, & 5-6) or non-adjacent letters two positions apart (i.e., Positions 2-5, & 3-6). A 2 X 2 within-participants factorial design was configured with Priming (transposition vs. substitution) and Distance (adjacent letters vs. non-adjacent letters) as main factors for both word and nonword stimuli. Examples of prime-target word pairs included “article – ARTICLE” and “aqnicle - ARTICLE” for the adjacent transposition and double substitution conditions respectively, and “actirle – ARTICLE” and “aqtinle – ARTICLE” for the non-adjacent transposition and double-substitution conditions, respectively. Examples of prime-target nonword pairs included “batrule-BARTULE” and “bagdule-BARTULE” for the adjacent transposition and double substitution conditions respectively, and “balture-BARTULE” and “bagtude-BARTULE” for the non-adjacent transposition and double substitution conditions, respectively. All word and nonwords targets stimuli and their corresponding prime stimuli across all experimental conditions are given in Appendix A and B respectively. Four lists of experimental trials were created with different pseudo-randomizations using the constraints that each target stimulus appeared once in each list and in all the experimental conditions across all lists. This design ensured that each experimental condition was equally represented throughout the experiment (i.e., 48 repetitions per list) and that the grand average ERP comparisons between conditions always involved the same and the entire set of target stimuli. Following a practice session of 16 trials, each participant was assigned to a stimulus list in a counterbalanced order. Experimental trials were presented in a random order and following the presentation of 48 trials participants were given the opportunity to rest.

Procedure

A masked sandwich priming lexical decision task was used. Participants were run individually in a sound-attenuated and dimly illuminated room after completing informed consent and handedness forms. Each participant sat comfortably 155 cm in front of an 18” monitor. Visual stimuli were displayed at high contrast as white letters on a black background in an 18-point Courier New font subtending 1.11 degrees of horizontal visual angle. The trial sequence followed in the experiment is illustrated in Figure 2. Each trial began with the presentation of a mask in the middle of the screen for 500ms. The mask was formed by 9 hash marks, sufficiently long to cover over and beyond primes. Two vertical lines were also positioned centrally above and below the mask indicating the point of fixation. The mask was replaced at the same location with a first prime comprising the target stimulus itself in upper case for 33ms. The first prime was immediately followed by the experimental prime in lower case for 50ms. The target stimulus then appeared in upper case (i.e. identical to the first prime) for 500ms. Participants were required to indicate as quickly and as accurately as possible whether the target stimulus spelled a French word or not by pressing a response key in their right or left hand respectively. The trial ended with the presentation of a blank screen for 2000ms. On every other trial, a stimulus (in the form of the letter ‘C’) appeared in the middle of the screen for 2500ms allowing participants to blink their eyes. The next trial followed a 500ms blank screen interval.

ERP Recording—The electroencephalogram (EEG) activity was recorded continuously through the ActiveTwoBiosemi system from 64 electrodes mounted on an elastic cap

(Electro-Cap Inc.) and positioned according to the 10-10 international system (American Clinical Neurophysiology Society, 2006). Two additional electrodes were (CMS/DRL nearby PZ) were used as online reference (for complete description, see Schutter, Leitner, Kenemans, & van Honk, 2006; www.biosemi.com). The montage included 10 midline sites and 27 sites over each hemisphere. In addition to scalp electrodes, two electrodes were used to monitor eye movements and blinks (one attached to at the right canthus and one below the left eye), and two electrodes were used for an offline re-referencing (attached to behind the ears on mastoid bone). EEG activity was amplified using an ActiveTwoBiosemi amplifier (DC 67 Hz bandpass, 3db/octave) and was continuously sampled (24 bit sampling) at a rate of 256 Hz throughout the experiment. EEG was filtered offline (20 Hz low-pass, 24 dB/octave) using EEGLAB software (Delorme & Makeig, 2004). All 64 electrode sites were referenced offline to the average of the right and left mastoids.

ERP Data and Analysis—ERP data were calculated by averaging the EEG time-locked to a point 100 ms pre-target onset and lasting until 600 ms post-target onset. The mean voltage of each epoch at each electrode was used as the baseline². Epochs with eye movements, blinks, or electrical activities greater than $\pm 75 \mu\text{V}$ were rejected. To maintain an acceptable signal-to-noise ratio, a lower limit of 32 artifact-free trials per participant per experimental condition was set. Overall, 3.7% of the trials were rejected.

Separate ERPs were formed for the four experimental word conditions defined by the factorial combination of Priming (target words preceded by transposition or substitution primes), and Distance (target words preceded by primes changed in adjacent or non-adjacent positions). The main analysis approach involved measuring mean amplitudes in three consecutive post-target onset latency windows and included 200-250ms (early N250), 250-300ms (late N250) and 300-500ms (N400). Repeated measures ANOVAs were run in each of these time windows, with mean amplitude as the dependent variable. Three anterior (F3, Fz, F4), three middle (C3, Cz, C4) and three posterior (P3, Pz, P4) electrode sites were chosen for analysis providing as such ANOVA factors of laterality (left vs. center vs. right) and anteroposterior (anterior vs. middle vs. posterior). This analysis approach has been successfully used in several previous studies (e.g., Grainger & Holcomb, 2009a; Grainger, Kiyonaga, Holcomb, 2006) and when paired with voltage maps computed across all sites is believed to offer the best combination of thorough yet easily comprehensible analyses (Grainger & Holcomb, 2009a).

Results

Behavioral Data

All correct lexical decisions less than 2000 ms post-target onset (98.6% of the data) and response accuracy were included in the behavioral analyses. 2 (Priming) X 2 (Distance) within-groups ANOVAs were conducted separately on the mean RTs and accuracy for word

²The mean voltage value of the epoch starting 100ms pre-target onset until 600ms post-target onset was used as a baseline correction because the more conventional use of a pre-target interval resulted in differences between conditions upon target onset. This is probably due to the EEG activity induced by the successive presentation of the target and prime preceding target onset in the sandwich priming technique. It is important to note that the overall pattern of results was not altered by the application of the mean epoch as a baseline correction compared to when pre-target intervals were used.

and nonword stimuli. Mean RTs and percentage of correct responses to words and nonwords for each of the two types of prime changes across adjacent and non-adjacent positions of change are presented in Table 1.

For words, analyses on mean RT revealed that the main effect of Priming ($F_1(1, 19) = 31.85, p < .001$; $F_2(1, 191) = 33.93, p < .001$) was significant whereas the main effect of Distance ($F_1(1, 19) = .49, p = .49$; $F_2(1, 191) = .49, p = .48$) was not. Overall, participants responded faster to target words following TL compared to substitution primes. Moreover, there was a significant 2-way interaction between Priming and Distance ($F_1(1, 19) = 6.04, p < .05$; $F_2(1, 191) = 6.39, p < .05$) reflecting the greater priming effects for adjacent compared with non-adjacent transpositions. Follow-up analyses revealed significant priming effects (i.e., the difference between TL and substitution primes) for both adjacent TL primes ($F_1(1, 19) = 58.68, p < .001$; $F_2(1, 191) = 37.03, p < .001$) and non-adjacent TL primes ($F_1(1, 19) = 5.84, p < .05$; $F_2(1, 191) = 5.58, p < .05$). Statistical analyses on mean accuracy for word stimuli revealed a significant main effect of Priming ($F_1(1, 19) = 25.82, p < .001$; $F_2(1, 191) = 20.11, p < .001$). Overall, participants responded more accurately to target words following TL compared to substitution primes.

For nonwords, analyses on mean RT revealed that the main effect of Priming ($F_1(1, 19) = 5.21, p < .05$; $F_2(1, 191) = 4.06, p < .05$) was significant whereas the main effect of Distance ($F_1(1, 19) < .01, p = .98$; $F_2(1, 191) = .44, p = .51$) was not. Overall, participants responded faster to nonwords following TL compared to substitution primes. Moreover, there was a significant 2-way interaction between Priming and Distance ($F_1(1, 19) = 11.39, p < .01$; $F_2(1, 191) = 7.02, p < .01$). Analysis of simple main effects of the interaction revealed a priming effect for nonwords following primes changed in adjacent positions only ($F_1(1, 19) = 11.82, p < .01$; $F_2(1, 191) = 10.27, p < .01$). Statistical analyses on mean accuracy for nonword stimuli revealed no significant effects.

Electrophysiological Data

Word stimuli—The exclusion of erroneous behavioral trials preceded the treatment and analysis of electrophysiological data. ERP waveforms for each of the experimental conditions time-locked to target word stimuli at the nine electrode sites used in the statistical analyses are plotted in Figure 3. Voltage maps formed from all 64 scalp sites contrasting the different type of priming effects within the three post-target onset latency windows (200-250ms, 250-300ms, and 300-500ms) are plotted in Figure 4. For each of these measurement windows, ANOVAs on mean amplitude were conducted following a 2 (Priming) X 2 (Distance) X 3 (Anteroposterior) X 3 (Laterality) repeated measures design. ANOVAs were performed using the Greenhouse-Geisser epsilon correction for non-sphericity (Jennings & Wood, 1976) to all repeated measures with more than one degree of freedom in the numerator (corrected p values are reported). We only report results concerning the main effect of Priming and the interaction of this factor with Distance, as well as higher-order interactions with these two variables and the two distributional variables (Anteroposterior and Laterality).

200-250ms target epoch: In this epoch, there was no main effect of Priming ($F(1,19) = 1.68, p = .21$). However, there was a marginally significant 2-way interaction between Priming and Distance ($F(1,19) = 3.83, p = .07$), which was further qualified by a significant higher-order interaction between Priming, Distance and Laterality ($F(2,38) = 6.90, p < .01$). Follow-up analyses of this triple interaction revealed that the Priming X Distance interaction was only significant over right hemisphere sites: ($F(1,19) = 6.02, p < .05$). Adjacent TL primes produced a priming effect that was significant on electrode sites over the right hemisphere ($F(1,19) = 4.60, p < .05$), whereas non-adjacent TL primes failed to produce any priming ($F(1,19) = .21, p = .65$). This interaction is illustrated in Figure 4.

250-300ms target epoch: In this time window, the analysis of ERPs to word targets revealed a main effect of Priming ($F(1,19) = 14.26, p < .01$) with substitution primes producing a more negative-going waveform than TL primes across both adjacent and non-adjacent positions of change (see Figure 3). The effect of priming was significant for both adjacent ($F(1, 19) = 7.28, p < .05$) and non-adjacent ($F(1, 19) = 11.90, p < .01$) TL primes. Furthermore, there was a significant interaction between Priming, Anteroposterior and Laterality ($F(4, 76) = 3.20, p < .05$). This interaction was due to the priming effect being more prominent on anterior-right electrode sites ($F(1, 19) = 22.57, p < .001$; see Figure 4). The interaction between Priming and Distance was not significant ($F(1, 19) = 1.24, p = .28$).

300-500ms target epoch: The analyses in this final time window revealed a main effect of Priming ($F(1,19) = 6.71, p < .05$). Furthermore, there was a significant 2-way interaction between Priming and Distance ($F(1,19) = 11.74, p < .01$), which was qualified further by the significant higher order interaction between Priming, Distance and Laterality ($F(2,38) = 7.54, p < .01$). Follow-up analyses revealed nevertheless that the critical Priming X Distance interaction was significant for scalp sites on the left: $F(1,19) = 5.06, p < .05$; in the centre: $F(1,19) = 14.10, p < .01$; and on right: $F(1,19) = 17.22, p < .01$. Overall, priming effects were only significant for adjacent transpositions ($F(1,19) = 12.85, p < .01$), with no significant priming seen for non-adjacent transpositions ($F(1,19) = .06, p = .81$).

Estimated onset of priming effects: We compared the ERPs generated at the Fz electrode site so as to estimate the difference between the onset of adjacent and non-adjacent TL priming. Separate ANOVAs were performed by using Priming (transposition vs. substitution) as a repeated measures independent variable for adjacent and non-adjacent positions of change. These analyses were conducted on the mean amplitude on all successive data points measured from 50ms pre-target onset to 500ms post-target onset with an approximate distance of 4ms between them. The onset of divergence between the ERPs generated by transposition and substitution (i.e., priming) was determined when at least 15 consecutive F values were significant ($p < .05$) (Rugg, Doyle, & Wells, 1995; Thorpe, Fize, & Marlot, 1996). For adjacent TL priming this was the case at 219ms post-target onset ($F(1,19) = 4.59, p < .05$) at electrode Fz. However, at the same electrode site the onset of non-adjacent TL priming emerged at 258ms post-target onset ($F(1,19) = 6.88, p < .05$).

Nonword stimuli—As with the word stimuli, the ERP data for nonword stimuli were analyzed within the same three post-target onset latency windows (200-250ms, 250-300ms,

and 300-500ms) and following the same ANOVA repeated measures design. As with the words, the exclusion of erroneous behavioral trials preceded the treatment and analysis of electrophysiological data for nonwords. In all three measurement windows the main effect of Priming was not significant ($p > .52$), and there was no significant interaction between Priming and Distance ($p > .36$). Furthermore, there were no significant higher-order interactions between Priming, Distance and Anteroposterior ($p > .18$) or between Priming, Distance and Laterality ($p > .54$; see Figure 4).

Discussion

We compared effects of adjacent and non-adjacent TL primes relative to the corresponding double-substitution primes in a sandwich priming study with ERP recordings. The non-adjacent TLs were separated by two letters. For word targets, non-adjacent priming effects were significant in the RT data, but these effects were significantly smaller than non-adjacent priming effects, thus replicating the prior work of Perea et al. (2008). In the ERP data, adjacent TL priming emerged earlier than non-adjacent priming, at around 200 ms post-target onset, and adjacent TL primes continued to show robust priming up to 500 ms post-target onset. The onset of the adjacent TL priming effect corresponds approximately to what was observed by Grainger et al. (2006) using standard masked priming. Non-adjacent priming effects, on the other hand, emerged at around 250 ms post-target onset and were very short-lived, being significant only in the 250-300 ms time-window. These different time-courses are evident in the voltage maps shown in Figure 4. Non-adjacent TL primes show a very different time-course from adjacent TL primes, revealing both a quantitatively and qualitatively different pattern of priming effects. Nonword targets only showed an effect of adjacent TL primes in the behavioral data. In what follows, we first discuss how these results can be accounted for by the model presented in the Introduction (Figure 1). We then discuss how alternative models might be able to capture these findings, and follow with a discussion of the importance, or not, of distinguishing positional flexibility from positional noise.

According to the theoretical framework presented in the Introduction and illustrated in Figure 1, the early adjacent TL priming effect is the result of positional noise operating on location-specific letter representations. Gaussian noise would generate positional uncertainty of limited spatial extent such that only adjacent transpositions can influence processing at this level. This captures the pattern of TL priming effects seen in the 200-250 ms time-window, where only adjacent TL primes had an effect. This pattern is in line with the results obtained with concatenated and hyphenated subset primes, showing that only hyphenated primes influenced target word processing in the 200-250 ms time-window (Grainger & Holcomb, 2009a; Ktori et al., 2012). Furthermore, prior to 200 ms, the evidence from ERP masked priming experiments suggest that the bulk of effects are being driven by prime-target visual overlap. Thus, for example, Chauncey, Holcomb, and Grainger (2008) found that a change in font across primes and targets affected repetition priming effects on the N/P150 component, a component that peaks at around 150 ms post-target onset, but did not affect priming on the N250 component (see Petit, Midgley, Holcomb, & Grainger, 2006, for a similar estimate of the timing of visual effects with single letter stimuli). Thus, while the earlier N/P150 component likely reflects the retinotopic mapping of visual features onto

letter identities, the early phase of the N250 component likely reflects processing at the level of location-specific letter representations. In Figure 12 of their review article, Grainger and Holcomb (2009b) described a tentative association of ERP components modulated by masked priming with component processes in visual word recognition. The present analysis fits well in this framework, with the peak of the N/P150 component corresponding to the mapping of visual features onto location-specific letter representations, the rise of the N250 component (early N250) corresponding to the mapping of location-specific letters onto location-invariant sublexical representations, and the fall of the N250 (late N250) corresponding to the mapping of location-invariant sublexical orthographic representations onto whole-word representations (see Grainger & Holcomb, 2009b, p. 144).

Subsequent to processing at the location-specific letter level, TL priming is hypothesized to be generated by location-invariant word-centered orthographic representations that are sensitive to both adjacent and non-adjacent transpositions. This accounts for the emergence of non-adjacent TL priming in this time-window, and the continued influence of adjacent TL primes. Contrary to our predictions, however, there was no evidence for non-adjacent TL priming in the N400 time-window, whereas adjacent TL primes continued to produce strong effects here. Indeed the most striking aspect of the present results is the rather short-lived nature of non-adjacent TL priming, being evident only in the 250-300 ms time-window. One possible explanation for the short-lived nature of this effect is that non-adjacent TL primes contain many letter combinations that mismatch with the target (e.g., ACTIRLE-ARTICLE: CT, CI, CR, TR, IR). If these bottom-up mismatches were to provide inhibitory input to whole-word representations, and assuming that inhibitory bottom-up influences are slower-acting than excitatory effects, then this could lead to a decrease in non-adjacent TL priming effects once they have emerged.

The explanation of the observed pattern of ERP priming effects offered above, appeals to two distinct mechanisms thought to be responsible for TL effects: positional noise and positional flexibility. Considerations of parsimony force us to question whether or not a single mechanism could account for the present findings. Indeed, apart from open-bigram coding, all other current explanations of TL effects appeal to positional noise operating on a letter position coding mechanism that would otherwise not generate TL effects (Davis, 2010; Fischer-Baum et al., 2011; Gomez et al., 2008; Norris et al., 2010). Since all these models predict that adjacent TL priming should be greater than non-adjacent TL priming, then it can be argued that the greater overall magnitude of adjacent TL priming will translate into an earlier onset in ERP priming effects. Alternatively, if these models were to adopt the distinction between location-specific gaze-centered letter representations, and location-invariant word-centered representations, then the absence of non-adjacent priming in the early time-window could be accommodated by a reduction in the amount of positional noise affecting location-specific letters. Finally, in order to account for the short-lived nature of non-adjacent ERP priming effects, these models could appeal to the same bottom-up mismatch mechanism as discussed above, since non-adjacent TLs provide greater evidence for the presence of letters in the incorrect positions. Therefore, in principle, single-mechanism models can account for the present findings.

One might therefore question the need to add a second mechanism, positional flexibility, in order to account for TL effects. We would point out, however, that single mechanism accounts have other hurdles to cross, such as evidence that the size of TL effects is greater for letters compared with digit and symbol stimuli (Duñabeitia et al., 2012; Massol et al., 2013). Most important is that the Duñabeitia et al. (2012) study also demonstrated qualitative differences in TL effects as revealed in ERP recordings. In that study, an early effect of character transposition was mostly evident for letter stimuli, with stimulus-independent effects only emerging at around 350 ms post-stimulus onset. Furthermore, a recent study has shown that TL priming effects actually increase in size during primary education (grades 1 to 5), at least when the RT data are transformed in order to accommodate differences in overall RTs across age groups (Ziegler, Bertrand, Lété, & Grainger, 2014). While one might expect positional noise to decrease and not increase with age, Hannagan and Grainger (submitted) have shown that a simple Perceptron network, trained to associate open-bigram input representations with whole-word output representations, also exhibits an increase in the size of TL effects with training.

Finally, within the dual-route framework for orthographic processing, the finding that adjacent but not non-adjacent TL primes facilitated lexical decision responses to nonword targets, suggests that the quality of information in precise position coded letters influences the speed with which a nonword decision can be made. It is this orthographic information that could be used in a spelling-check mechanism interacting with whole-word orthographic representations. However, the fact that there was no clear evidence for such priming effects in the ERP data suggests that the behavioral results should be interpreted with caution. Furthermore, the absence of non-adjacent TL priming in the N400 time-window in the presence of a significant behavioral effect suggests that participants in our experiment were basing their lexical decisions on activity in whole-word orthographic representations (e.g., Grainger & Jacobs, 1996), and not at the level of semantic representations (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996).

In conclusion, we have shown that adjacent and non-adjacent TL priming differ not only in terms of the size of behavioral effects, with adjacent priming being significantly greater than non-adjacent effects, but also in terms of the time-course of priming effects as revealed in our ERP recordings. Adjacent TL priming emerged earlier than non-adjacent TL priming, and the adjacent priming effects lasted longer, extending into the N400 time window. Further research is required in order to determine the cause of the short-lived non-adjacent priming effect, research that should help determine whether or not positional flexibility, over and above positional noise, is necessary in order to account for the full range of TL effects.

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Appendix A: Word Targets and Corresponding Prime Stimuli across Experimental Conditions

The items are arranged in quintuplets in the following order: target word, adjacent transposed-letter prime, adjacent double substitution prime, non-adjacent transposed-letter prime, and non-adjacent double substitution prime.

ABANDON, abadnon, abatcon, adanbon, atancon; ABSENCE, asbence, arxence, ansebece, arsexce; ABSENTE, asbente, amgente, ansebte, amsegte; ABSURDE, asburde, atlurde, arsubde, atsulde; ACTRICE, actirce, actubce, aitrce, autrbce; AMATEUR, amaetur, amaihur, aeatmur, aiatbur; AMICALE, amiclae, amicroe, amlcaie, amrcae; AMUSANT, amusnat, amusret, amnsaut, amrsaet; ANALYSE, anaylse, anaorse, ayalnse, aoalrse; ARTICLE, atricle, aqnicle, actirle, aqtnle; AUBERGE, abuerge, apierge, arbeuge, apbeige; AVEUGLE, aveulge, aveumce, ageuvle, ameucle; BAGNOLE, bangole, bcunole, balnoge, bacnore; BALANCE, balacne, balahme, bacanle, bahanme; BARAQUE, barqaue, barcoue, bauaqre, baoaqce; BARBIER, bariber, barocer, baebirr, baobir; BONHEUR, bonehur, bonasur, bouhenr, boahesr; BOUCHER, boucehr, boucagr, bhucor, bgucaer; BOUCHON, bouhcon, bousron, bhucoon, bsuceon; BRIGADE, briagde, briosde, baigrde, boigsde; BRIQUET, briuqet, briacet, buiqret, baiqet; BRUTALE, brutlae, brutmoe, bautrle, boutmle; CABINET, cabniet, cabruet, cnbiaet, crbiuet; CADAVRE, cadarve, cadasne, caravde, casavne; CAPABLE, capalbe, capatre, calabpe, catabre; CAPITAL, capiatl, capiunl, ctpiaal, cnpiual; CAPORAL, capoarl, capoibl, crpoaal, cbpoal; CAPRICE, carpice, cmorice, cacripe, camribe; CASERNE, caesrne, caotrne, crseane, ctseone; CENTRAL, centarl, centiwl, crntal, cwnl; CERTAIN, ceratin, cerulin, ceitarn, ceutaln; CHAGRIN, chargin, chalbin, craghin, clagbin; CHALEUR, chaelur, chaitur, cealhur, cialtur; CHAMBRE, chabmre, chagtre, cbamhre, cgamtre; CHANSON, chasnon, charpon, csanhon, cranpon; CHARBON, chabron, chadlon, cbarhon, cdarlon; CHARIOT, chairot, chaunot, ciarhot, cuarnot; CHEMISE, chemsie, chemnae, ciemhse, caemnse; CIRCUIT, cicruit, cinmuit, ciicurt, ciacunt; CLIENTE, clietne, clierse, cnietle, crieste; COLONEL, colnoel, colviel, coeonll, coionvl; COLONIE, colnoie, coltuie, coionle, couonte; COMPLET, compelt, compast, clmpoet, csmpt; CONFLIT, confilt, confejt, clnfoit, cjnfeit; CONSEIL, conesil, conahil, coisenl, coasehl; CONTACT, cotnact, cojract, coctant, cojtart; CONTRAT, contart, contust, crntoat, csntuat; COSTUME, cotsume, conjume, comtuse, contuje; COUCHER, coucehr, coucanr, chucor, cnucaer; COURANT, cournat, courdet, conraut, codraet; COUTUME, coutmue, coutdie, comtue, codtue; COUTURE, coutrue, coutvae, cortue, covtue; COUVENT, covuent, corient, conveut, corveit; CRAVATE, cravtae, cravsoe, caavrt, coavste; CRISTAL, critsal, crindal, ctisral, cnisdal; CROCHET, crohcet, crolvet, chocret, clovret; CUISINE, cuisnie, cuisvoe, cunsiie, cuvsioe; DEMANDE, demnade, demcide, dnmaede, dcmaide; DEMEURE, demerue, demecoe, dereume, deceute; DERNIER, denrier, detcier, deenirr, deanitr; DIAMANT, diamnat, diamgut, dinmaat, digmaut; DIRECTE, drecte, dxucte, dcreite, dxreute; DISCRET, discert, discapt, drsciet, dpscaet; DISPUTE, dipsute, dilmute, ditpuse, dilpume; DIVORCE, diovrce, diahrce, drvoice, dhvoace; DOCTEUR, docetur, docimur, douter, doitemr; ENDROIT, endorit, endacit, eodrnit, eadrcit; ENTRAIN, entarin, entulin, eatrnin, eutrlin; ESCLAVE, esclave, englave, esvlace, esnlage; ESCORTE, ecsorte, ehxorte, ercoste, ehcoxe; ESTOMAC,

etsomac, ernomac, emtosac, ertonac; EXEMPLE, exepmle, execslle, epemxle, ecemsle; FACTEUR, facetur, facilur, fautecr, faitelr; FALAISE, falasie, falanue, fasaile, fanaite; FAMEUSE, fmaeuse, ftieuse, faseume, fateuje; FARDEAU, fadreau, fanceau, faaderu, faidenu; FERMIER, femrier, feslier, feomirr, feomisr; FLINGUE, flignue, flivcue, fginlue, fvincue; FORMULE, fomrule, foctule, folmure, focmute; FORTUNE, fotrune, fomlune, fonture, fomtule; FOULARD, foluard, foneard, forlaud, fonlaed; FRAGILE, fraglie, fragnue, fiagrlle, fuagnle; FRANGIN, fragnin, fradtin, fganrin, fdantin; GARDIEN, gradien, gbodien, gaedirn, gaodibn; GOUDRON, gourdon, gouclon, grudoon, gcudaon; GRATUIT, gartuit, goptuit, guatrit, goatpit; GRECQUE, greqcue, gresnue, gqecrue, gsecnue; GRENADE, grendae, grencue, gaenrde, guencde; HORIZON, horiozn, horiatn, hzrioon, htiaon; HOSPICE, hopsice, hovtice, hocpise, hovpite; HOSTILE, hotsile, hpatile, holtise, hoptice; IGNOBLE, ingoble, irmoble, ibnogle, irnomle; INDIGNE, idnigne, ilrigne, igdinne, ildirne; INJUSTE, ijnuste, ilruste, intusje, inlusre; INQUIET, inuqiet, inociet, ineuiqt, inouict; INSECTE, isnecte, imrecte, icsente, imserte; INSULTE, isnulte, ihpulte, ilsunte, ihsupte; INTERNE, itnerne, icgerne, irtenne, ictegne; INUTILE, iuntile, iastile, inltiue, instiae; ITALIEN, itailen, itaoren, ialten, ioalren; IVROGNE, irvogne, ifcogne, igrovne, ifrocne; JOURNAL, jouranl, jourevl, jnuoral, jvureal; JUSTICE, jutsice, jrotice, juctise, jurtine; LECTURE, letcure, lesbure, lertuce, lestube; LUGUBRE, lugurbe, lugutce, lurubge, lutubce; MACHINE, mahcine, mavline, manhice, mavhile; MAGASIN, magsain, magvein, maiasgn, maeasvn; MALADIE, maldaie, malroie, maiadle, maoadre; MALAISE, malasie, malaboe, masaille, mabaite; MALHEUR, mlaheur, mfoheur, mauhelr, maohefr; MANTEAU, matneau, mahpeau, maatenu, maitehu; MARTEAU, matreau, manseau, maateru, maotenu; MAXIMUM, maxiumm, maxielm, mmxiaum, mlxieum; MENTION, mnetion, mration, meotinn, meatirn; MEURTRE, merutre, mepitre, merrtue, meprtie; MINABLE, minbale, minrole, mbnaile, mrnaole; MINIMUM, minmium, mintaum, miuimnm, miaimtm; MIRACLE, mriacle, mbuacle, mcraile, mbraule; MODERNE, moedrne, mlierne, mrdeone, mldeine; MODESTE, modsete, modgute, msdeote, mgdeute; MOINDRE, monidre, mojadre, mdinore, mjinare; MONSTRE, mosntre, mopctre, morstne, mopstce; MUSIQUE, musiuqe, musiote, mqsiiue, mtsioue; NATUREL, natuerl, natuovl, nrtuael, nvtuoel; NORMALE, nomrale, notcale, nolmare, notmace; OBSCURE, osbcure, otmcure, obrcuse, obtcume; OPINION, oipnion, oexnion, oiinpon, oeinxon; ORIGINE, orignie, origmae, oiiqrne, oaigmne; OUVERTE, ovuerte, osierte, orveute, osveite; PARKING, pakring, patsing, pankirg, patkisg; PARQUET, paruqet, parocet, paequrt, paoquct; PASTEUR, pasetur, pasocur, pautesr, paotecr; PATIENT, ptaietn, pmuient, paniett, pamiedt; PEINTRE, penitre, pesutre, ptinere, psinure; PELOTON, pleoton, psaoton, ptloeon, psloaon; PELOUSE, pleouse, pdaouse, pesoule, pedoute; PENDULE, pednule, pebxule, peldune, pebduxe; PENSION, pnesion, ptasion, peosinn, peasitn; PLACARD, placrad, placbod, paaclrd, poacbrd; PLAFOND, plaofnd, plaehnd, poafnd, peafhnd; PLAISIR, palisir, penisir, psailir, pnaifir; PLANCHE, placnhe, plasthe, pcanlhe, psanthe; PLANQUE, plaqnue, plafrue, pqanlue, pfanrue; POIGNET, poigent, poigalt, pnigoet, pligaet; PORTAIL, protail, pdetail, poitarl, poetadl; PORTANT, potrant, posbant, pontart, postabt; PORTIER, protier, pnatier, poetirr, poatinr; POSTALE, potsale, pbutale, poltase, pobtade; PRODIGE, proidge, proalge, prgdioe, prldiae; PROFOND, profnod, proftid, poofrnd, pioftnd; PRUDENT, prudnet, prudsat, peudrnt, paudsnt; RALENTI, raelnti, rfoenti, rnleati, rfleoti; REMPLIE, rmeplie, rjaplie, rlmpeie, rjmpaie; RENFORT, refnort, rvifort, rerfont, revfobt; RESTANT, retsant,

relvant, rentast, reltavt; RETRAIT, rterait, rsurait, reiratt, reurast; ROBINET, rboinet, rlainet, rnbioet, rlbaiet; ROULANT, roluant, roseant, ronlaut, roslaet; SALAIRE, salarie, salatue, saraile, sataihe; SCIENCE, sciecne, scietre, sniecce, stierce; SECONDE, secnode, secride, sncoede, srcoide; SECTION, scetion, sxution, seotcn, seutixn; SEMAINE, smeaine, stoaine, senaime, setaire; SENTIER, setnier, sbatier, seetnr, seatibr; SERVICE, sevrice, sedbice, secvire, sedvibe; SILENCE, slience, stoence, snleice, stleoce; SORDIDE, sodride, sontide, soddire, sondite; STATION, sattion, sultion, siatton, suatlon; STUPIDE, sutpide, sanpide, siuptde, saupnde; SUBLIME, sulbime, sunrime, sumlibe, sunlire; SUICIDE, suicdie, suicpae, sudciie, supciae; SUIVANT, suviant, sufeant, sunvait, sufvaet; SUPERBE, spuerbe, sfaerbe, srpeube, sfpeabe; SURFACE, sufrace, suntace, sucfare, sunfate; SUSPECT, supsect, surlect, sucpest, surpelt; SYMBOLE, sybmole, scabole, sylbome, sycbone; TABLEAU, talbeau, tnileau, taalebu, tailenu; TABLIER, thalier, tnolier, taelibr, taolnr; TAMBOUR, tmabour, tnibour, taubomr, taibonr; TENSION, tnesion, trasion, teosinn, teasirn; TOUCHER, toucehr, toucibr, thucoer, tbucier; TRAVAIL, tarvail, tugvail, taavril, tuavgil; TRONCHE, trocnhe, tromshe, tconrhe, tmonshe; TROUBLE, troulbe, trounde, thourle, tnoudle; URGENCE, ugrence, umsence, ungerce, umgesce; VACARME, vacamre, vacadne, vamarce, vadarne; VERSION, vresion, vbysion, veosirn, vaysibn; VERTIGE, vetrige, vnotige, vegtire, ventice; VIOLENT, viloent, vicaent, vinleot, vicleat; VISIBLE, visilbe, visicte, vilibse, vicibte; VIVANTE, vivnate, vivcote, vnvaite, vcvaote; VOISINE, voisnie, voislue, vonsiie, volsiue

Appendix B: Nonword Targets and Corresponding Prime Stimuli across Experimental Conditions

The items are arranged in quintuplets in the following order: target word, adjacent transposed-letter prime, adjacent double substitution prime, non-adjacent transposed-letter prime, and non-adjacent double substitution prime.

ABACODU, abaocdu, abaildu, aoacbdu, aiacldu; ABLICHE, albiche, amviche, aclibhe, amlivhe; ACEMITE, acemtie, acemlue, aiemcte, auemlte; AFIMENT, afiemnt, afiusnt, aeimfnt, auimsnt; AGARTIN, agatrin, agavdin, atargin, avardin; ALVANDE, avlande, agpande, anvalde, agvapde; AMENTRE, ametnre, amebcre, atenmre, abencre; AMESAIS, ameasis, ameuris, aesmis, auesris; ANIGION, aingion, aulgion, anogiin, anugien; APTERSE, atperse, alcerse, artepe, altecse; ARLONTE, alronte, apmonte, anlorte, aplomte; ARNONTTE, anronte, agconte, annorte, agnocte; ARPACHE, aprache, alnache, acparhe, alpanhe; ARPASME, aprasme, alxasme, asparme, alpaxme; ASMARTE, amsarte, andarte, armaste, anmadte; ASPLITE, apslite, arqlite, astlipe, asrliqe; ATANODA, atandoa, atancua, aoantda, auancda; ATILIER, aitlier, auvlier, ailter, auilver; AUFANTE, afuante, ariante, anfaute, arfaite; AUMANTE, auamnte, auornte, anmaute, armaote; AVEILDA, aveidla, aveisna, aleivda, aseinda; BAPONRE, bapnore, baplure, bnpoare, blpoure; BARTULE, batrule, bagdule, balture, bagtude; BEAULER, beauehr, beauonr, blaueer, bnauoer; BLODIRE, bloidre, blounre, bioldre, buodnre; BOIDIRE, boidrie, boidhue, biidore, buidare; BORTION, botrion, boslion, bootirn, boatirn; BRILSER, brisler, brinmer, bsilrer, bnilmer; BRORAIS, broaris, broeqis, baorris, beorqis; BROUCHE, brouhce, broufse, bcourhe, bfoushe; CADIVIE, cdaivie, cruivie, cvdiaie, crdiuie; CANETIN, cantein, canboin, ctneain,

cbneoin; CARSION, carison, caruhon, caosirn, causihn; CARTEME, catreme, canfeme, camtere, cantefe; CASTICE, catsice, cadhice, cactise, cadtihe; CEINLET, ceilnet, ceivjet, clineet, cvinaet; CENURIE, cenruie, cenbaie, crnueie, cbnuaie; CHAFLET, chalfet, chanbet, clafhet, cnafbet; CHANIRE, chainre, chaovre, cianhre, coanvre; CHANTUE, chatnue, chalmue, ctanhue, clanmue; CHEMILE, chemlie, chemdoe, ciemhle, coemdle; CHESAIT, cheasit, cheudit, caeshit, cuesdit; CHODRAN, chordan, chotfan, crodhan, ctodfan; CHOGALE, choagle, choufle, caoghle, cuogfle; CHOLEUR, choelur, choinur, ceolhur, ciolnur; CHONCLE, chocnle, chotgle, cconhle, ctongle; CHOPIGE, choipge, choatge, ciophge, caoptge; CLENCRE, clecnre, clehbre, ccenlre, chenbre; COMNISE, connise, coprise, cosnime, copnire; COMPANE, copmane, codsane, conpame, codpase; COMPITE, copmite, codhite, cotpime, codpihe; CONELSE, cnoelse, ctaelse, clneose, ctnease; CONTASE, cotnase, cohase, costane, cohtale; CORTALS, cotrals, convals, coltars, contavs; COUBLER, coubelr, coubanr, cluboer, cnubaer; COUVARD, covuard, coliard, corvau, colvaid; CROILER, crolier, crobaer, cloirer, cboiver; CROSONS, crosnos, crosfis, coosrns, ciosfns; DAPISIE, dpaisie, druisie, dspiaie, drpiuie; DEGARNE, deagne, deitrne, drgaene, dtgaine; DERISME, dersime, dernome, dsrieme, dnriome; DETRONS, dertons, dempons, denrots, demrops; DIACAME, diacmae, diacloe, daacime, doacume; DOICHER, doichehr, doicahr, dhicoer, dsicaer; DONFLER, donfelr, donfamr, dlnfoer, dmnfaer; DONFLET, donfelt, donfigt, dlnfoet, dgnfiet; DONSAIS, donasis, donetis, doisans, doesats; DONSIRE, dosnire, dovtire, dorsine, dovsite; DONTEUR, donetur, donapur, douter, doatepr; DONTRER, donterr, donticr, drntoer, dcntier; DORMUTE, domrute, docvute, dotmure, docmuve; DORTRAI, dortari, dorten, drttoai, dnrteai; DRANQUE, draqnue, draspue, dqanrue, dsanpue; DRIOCHE, driohce, driongse, dciorhe, dgioshe; EFSAYER, efasyer, efolyer, eysafer, eosaler; ENFUTES, efnutes, elvutes, etfunes, elfuves; ERTROCE, etroce, elvroce, ercrote, erlrove; ESTRAIT, estarit, estuhit, eatrsit, eutrhit; FABERTE, fbaerte, fmuerte, frbeate, fmbeute; FAILEME, falieme, fatoeme, famleie, fatleoe; FAINIGE, faingie, faincue, fagnie, facniue; FALECRE, faelcre, fauscre, fcleare, fsleure; FARANIR, farnair, farteir, faianrr, faeantr; FAUTURE, fauture, fautlie, fartuue, faltuie; FAVERTE, favetre, favesne, faterve, faserne; FENSION, fnesion, flasion, feosinn, feasiln; FETUACE, fetucae, fetusie, fecuate, fesume; FORPAIT, fropait, fcupait, foipart, foupact; FRANDEX, fradnex, frasmex, fdanrex, fsanmex; FRANTRA, fratnra, fracqra, ftanrra, fcanqra; GLOURDE, gloudre, gloutve, groulde, gtouvde; GOLEFIT, goleft, goleuct, gfleoit, gcleuit; HATADRE, hatarde, hatamle, haradte, hamadle; INAPIDU, inapdiu, inapcou, indpiau, incpiou; INDIFLE, idnifle, ivpifle, ifdinle, ivdiple; INSMAN, insamin, insecin, iasmmn, iesmcin; INSTOME, isntome, irwtome, inmtose, inrtowe; JECOUSE, jecouse, jecomie, jesouce, jemoune; JEUCHER, jeuhcer, jeusler, jhuceer, jsucier; JEURICE, jeruice, jevoice, jecriue, jevrio; LONGLUT, longult, longect, lngout, lngout; LORIBLE, lorilbe, lorifve, lolibre, lofibve; LORTION, lotrion, lopfion, lootirn, loetipn; LOSISTE, lositse, losinre, lotisse, lonisre; LOURMER, lorumer, lohimer, lmuroer, lhurier; MABLIER, mbalier, mnulier, maelibr, maulinr; MAIMENS, mamiens, matoens, manmeis, matmeos; MAINLEZ, manilez, mavolez, mlineaz, mvinoez; MAITEND, matiend, maluend, manteid, malteud; MALTEUR, mlateur, mxiteur, mautelr, maitehr; MANCOUA, mnacoua, mtecoua, maucona, maecota; MAPRORE, marpore, mantore, marrope, manrote; MAPULAN, mauplan, maovlan, mlpuan, mvpuan; MARCOUA, mracoua, mticoua, maucora, maicota; MARTIFI, matrifi, maspifi, maftiri, mastipi; MATACLE, matalce, matanpe, malacte,

manacpe; MENITER, meinter, meabter, meitnr, meaitbr; MIRIEUR, miireur, miapleur, miuierr, miaiepr; MOLOYAL, moolyal, moedyal, moaoyll, moeoydl; MOLVAIS, mlovais, mxevais, moivals, moevaxs; MONGURE, mognure, mosvure, morgune, mosguve; MONLERA, molnera, mobsera, morlena, moblesa; MONRAIS, mnorais, mvurais, moirans, mouravs; NAISLAN, nailsan, naipgan, nlisaan, npisean; NAMERCE, namecre, nametle, nacerme, naterle; NOINFRE, nonifre, notafre, nfinore, ntinare; NOSINAL, nosianl, nosievl, nnsioal, nvsieal; OCTENDE, octedne, octelre, ontecde, olterde; ONTADRE, ontarde, ontalge, odtanre, oltagre; ORTRARE, otrrare, onmrare, orrrate, ornrame; PALONRE, palorne, palotve, paronle, patonve; PARQUEL, praquel, pniquel, paeurl, paiqunl; PARTINE, patrine, pabsine, pantire, pabtise; PASTION, psation, plution, paotism, pautilm; PASURME, pasumre, pasunhe, pamurse, panurhe; PENVRER, penrver, pencler, prnveer, pcnvaer; PERNAIS, prenaiss, pmunais, peinars, peunams; PERTION, pretion, plution, peotirm, peutilm; PICESPE, picepse, picegte, pipesce, pigeste; PLARINE, plarnie, plarmoe, piarlne, poarmne; PLAVERS, plavres, plavcus, peavlrs, puavcrs; PLUCHIR, pluheir, plutsir, phuclir, ptucsir; POGARDE, pogadre, pogalte, podarge, polarte; POLEURS, polerus, polecas, poreuls, poceuts; POLOUGE, pologue, polorie, pogoule, poroune; PORSAIT, prosait, pdesait, poisart, poesadt; PORTACT, potract, podsact, poctart, podtast; POSTARE, potsare, polbare, portase, poltabe; POSTIRE, potsire, ponjire, portise, pontije; POURTAL, porutal, pocital, pturoal, pcurial; PRENSIN, presnin, pretvin, psenrin, ptenvin; PRISORS, pirsors, pabsors, poisrrs, paisbrs; PROLOSA, prolsoa, provea, poolrsa, peolrsa; PRONETA, porneta, pulneta, peonrta, puonlta; PROVELS, porvels, pucvels, peovrls, puovcls; PUTERPE, putepre, putebne, puperte, puberne; RELIVEC, relievc, relitoc, reeivlc, reioitc; RENARTE, renatre, renalme, retarne, relarme; RENSION, rnesion, rlasion, reosinn, reasiln; RERATIN, rreatin, rmoatin, rtraein, rmraoin; RERIOLE, rreiole, rnuirole, reliore, reniote; REROTON, rreoton, rduoton, rtroeton, rdrouon; RESTAIL, rsetail, rvutail, reitasl, reutavl; REVERSE, revesne, revetde, reserve, retende; ROUVERE, rovuere, roxaere, rorveue, roxveae; SACONEL, scaonel, svionel, sncoael, svcoiel; SASAQUE, sasqaue, sasboue, sauqaue, saoaqbe; SAULORS, saluors, sateors, sarlous, satloes; SENSEAIE, senasie, senujie, seisane, seusaie; SENSION, serison, seralon, seosirn, seasiln; SETAIRE, steaire, sxoaie, seraite, sexaie; SICASON, sicsaon, sicduon, sscaion, sdcauon; SISENCE, sisecne, sisehppe, sicense, sihenpe; SIVOYER, svioyer, snaoyer, sieoyvr, siaoynr; SONVRIR, snovrir, spevrir, srnvoir, spnveir; SORDATE, sodrate, soncate, sotdare, sondace; SORMAIS, soramis, sorepis, soimars, soemaps; SORVAIS, soravis, sorugis, soivars, souvags; STETION, steiton, steamon, sietton, saetmon; SUCHANT, suhcant, suglant, sunhact, sughalt; SURLIVE, sulrive, suncive, suvlire, sunlice; SURVITE, suvrite, sumnite, sutvire, sumvine; TENVAIS, tenavis, tenuris, teivans, teuvans; TERDANT, tedrant, tegpant, tendart, tegdapt; TETOICE, tteoice, truoice, tecoite, teroise; TRALAIT, tarlait, tuclait, taalrit, tualcit; VENSAS, venasis, venotis, veisans, veosats; VERFINE, vefrine, vetcine, venfire, vetfice; VEULORS, veluors, vemiors, verlous, vemlois; VIPABLE, vipalbe, vipasne, vilabpe, visabne; VOUPLER, vopuler, voniler, vlupoer, vnupier; VRESQUE, vreqsue, vretmue, vqesrue, vtesmue.

References

Andrews S. Lexical retrieval and selection processes: Effects of TL confusability. *Journal of Memory and Language*. 1996; 35:775–800. doi:10.1006/jmla.1996.0040.

- Bruner JS, O'Dowd D. A note on the informativeness of parts of words. *Language and Speech*. 1958; 1:98–101. doi:10.1177/002383095800100203.
- Carreiras M, Duñabeitia JA, Molinaro N. Consonants and vowels contribute differently to visual word recognition: ERPs of relative position priming. *Cerebral Cortex*. 2009; 19:2659–2670. doi: 10.1093/cercor/bhp019. [PubMed: 19273459]
- Chambers SM. Letter and order information in lexical access. *Journal of Verbal Learning and Verbal Behavior*. 1979; 18:225–241. doi:10.1016/S0022-5371(79)90136-1.
- Chauncey K, Holcomb PJ, Grainger J. Effects of stimulus font and size on masked repetition priming: An ERP investigation. *Language and Cognitive Processes*. 2008; 23:183–200. doi: 10.1080/01690960701579839. [PubMed: 19590754]
- Davis CJ. The spatial coding model of visual word identification. *Psychological Review*. 2010; 117:713–758. doi: 10.1037/a0019738. [PubMed: 20658851]
- Delorme A, Makeig S. EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*. 2004; 134:9–21. doi: 10.1016/j.jneumeth.2003.10.009. [PubMed: 15102499]
- Duñabeitia JA, Dimitropoulou M, Grainger J, Hernández JA, Carreiras M. Differential Sensitivity of Letters, Numbers, and Symbols to Character Transpositions. *Journal of Cognitive Neuroscience*. 2012; 24:1610–1624. doi:10.1162/jocn_a_00180. [PubMed: 22185490]
- Ferrand L, New B, Brysbaert M, Keuleers E, Bonin P, Méot A, Augustinova M, Pallier C. The French Lexicon Project: Lexical decision data for 38,840 French words and 38,840 pseudowords. *Behavior Research Methods*. 2010; 42:488–496. doi:10.3758/BRM.42.2.488. [PubMed: 20479180]
- Fischer-Baum S, Charny J, McCloskey M. Both-edges representation of letter position in reading. *Psychonomic Bulletin & Review*. 2011; 18:1083–1089. doi: 10.3758/s13423-011-0160-3. [PubMed: 21935735]
- Fischer-Baum S, McCloskey M, Rapp B. Representation of letter position in spelling: Evidence from acquired dysgraphia. *Cognition*. 2010; 115:466–490. doi: 10.1016/j.cognition.2010.03.013. [PubMed: 20378104]
- Forster KI, Davis C. Repetition priming and frequency attenuation in lexical access. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 1984; 10:680–698. doi: 10.1037/0278-7393.10.4.680.
- García-Orza J, Perea M, Muñoz S. Are transposition effects specific to letters? *Quarterly Journal of Experimental Psychology*. 2010; 63:1603–1618. doi:10.1080/17470210903474278.
- Gómez P, Ratcliff R, Perea M. The overlap model: A model of letter position coding. *Psychological Review*. 2008; 115:577–600. doi:10.1037/a0012667. [PubMed: 18729592]
- Grainger J. Cracking the orthographic code: An introduction. *Language and Cognitive Processes*. 2008; 23:1–35. doi:10.1080/01690960701578013.
- Grainger J, Holcomb PJ. An ERP investigation of orthographic priming with relative-position and absolute-position primes. *Brain Research*. 2009a; 1270:45–53. doi:10.1016/j.brainres.2009.02.080. [PubMed: 19285966]
- Grainger J, Holcomb PJ. Watching the word go by: On the time-course of component processes in visual word recognition. *Language and Linguistics Compass*. 2009b; 3:128–156. doi:10.1111/j.1749-818X.2008.00121.x. [PubMed: 19750025]
- Grainger J, Jacobs AM. Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review*. 1996; 103:518–565. doi:10.1037/0033-295X.103.3.518. [PubMed: 8759046]
- Grainger J, Kiyonaga K, Holcomb PJ. The time-course of orthographic and phonological code activation. *Psychological Science*. 2006; 17:1021–1026. doi:10.1111/j.1467-9280.2006.01821.x. [PubMed: 17201781]
- Grainger, J.; van Heuven, WJB. Modeling letter position coding in printed word perception. In: Bonin, P., editor. *The Mental Lexicon*. Nova Science; New York: 2003. p. 1-23.
- Grainger J, Whitney C. Does the human mind read words as a whole? *Trends in Cognitive Sciences*. 2004; 8:58–59. doi:10.1016/j.tics.2003.11.006. [PubMed: 15588808]
- Grainger J, Ziegler JC. A dual-route approach to orthographic processing. *Frontiers in Psychology*. 2011; 2:54. doi:10.3389/fpsyg.2011.00054. [PubMed: 21716577]

- Hannagan, T.; Grainger, J. Orthographic learning and the developmental transposed-letter effect. 2014. Manuscript submitted for publication
- Hannagan T, Grainger J. Protein Analysis Meets Visual Word Recognition: A Case for String Kernels in the Brain. *Cognitive Science*. 2012; 36:575–606. doi:10.1111/j.1551-6709.2012.01236.x. [PubMed: 22433060]
- Jennings JR, Wood CC. The ϵ -adjustment procedure for repeated measures analysis of variance. *Psychophysiology*. 1976; 13:277–278. doi:10.1111/j.1469-8986.1976.tb00116.x. [PubMed: 1273235]
- Ktori M, Grainger J, Dufau S, Holcomb PJ. The “electrophysiological sandwich”: A method for amplifying ERP priming effects. *Psychophysiology*. 2012; 49:1114–24. doi:10.1111/j.1469-8986.2012.01387.x. [PubMed: 22681238]
- Lee CH, Taft M. Are onsets and codas important in processing letter position? A comparison of TL effects in English and Korean. *Journal of Memory and Language*. 2009; 60:530–542. doi:10.1016/j.jml.2009.01.002.
- Lupker SJ, Davis CJ. Sandwich priming: A method for overcoming the limitations of masked priming by reducing lexical competitor effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2009; 35:618–639. doi:10.1037/a0015278.
- Massol S, Duñabestia JA, Carreiras M, Grainger J. Evidence for letter-specific position coding mechanisms. *PLoS ONE*. 2013; 8(7):e68460. doi:10.1371/journal.pone.0068460. [PubMed: 23844204]
- New B, Pallier C, Brysbaert M, Ferrand L. Lexique 2: A New French Lexical Database. *Behavior Research Methods, Instruments, & Computers*. 2004; 36:516–524. doi:10.3758/BF03195598.
- Norris D. The Bayesian reader: explaining word recognition as an optimal Bayesian decision process. *Psychological Review*. 2006; 113:327–357. doi:10.1037/0033-295X.113.2.327. [PubMed: 16637764]
- Norris D, Kinoshita S, van Casteren M. A stimulus sampling theory of letter identity and order. *Journal of Memory and Language*. 2010; 62:254–271. doi:10.1016/j.jml.2009.11.002.
- O'Connor RE, Forster KI. Criterion bias and search sequence bias in word recognition. *Memory & Cognition*. 1981; 9:78–92. doi:10.3758/BF03196953. [PubMed: 7231172]
- Perea M, Carreiras M. Do TL similarity effects occur at a prelexical phonological level? *Quarterly Journal of Experimental Psychology*. 2006; 59:1600–1613. doi:10.1080/17470210500298880.
- Perea M, Carreiras M. Do orthotactics and phonology constrain the TL effect? *Language and Cognitive Processes*. 2008; 23:69–92. doi:10.1080/01690960701578146.
- Perea M, Duñabestia JA, Carreiras M. TL priming effects for close versus distant transpositions. *Experimental Psychology*. 2008; 55:397–406. doi:10.1027/1618-3169.55.6.397.
- Perea M, Lupker SJ. Does judge activate COURT? TL confusability effects in masked associative priming. *Memory and Cognition*. 2003; 31:829–841. doi:10.3758/BF03196438. [PubMed: 14651292]
- Perea M, Lupker SJ. Can CANISO activate CASINO? TL similarity effects with nonadjacent letter positions. *Journal of Memory and Language*. 2004; 51:231–246. doi:10.1016/j.jml.2004.05.005.
- Perea M, Rosa E, Gómez C. The frequency effect for pseudowords in the lexical decision task. *Perception and Psychophysics*. 2005; 67:301–314. doi:10.3758/BF03206493. [PubMed: 15971693]
- Petit JP, Midgley KJ, Holcomb PJ, Grainger J. On the time-course of letter perception: A masked priming ERP investigation. *Psychonomic Bulletin & Review*. 2006; 13:674–681. doi: [PubMed: 17201369]
- Plaut DC, McClelland JL, Seidenberg MS, Patterson K. Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review*. 1996; 103:56–115. doi:10.1037/0033-295X.103.1.56. [PubMed: 8650300]
- Rayner K, White SJ, Johnson RL, Liversedge SP. Reading words with jumbled letters: There is a cost. *Psychological Science*. 2006; 17:192–193. doi: 10.1111/j.1467-9280.2006.01684.x. [PubMed: 16507057]

- Rugg MD, Doyle MC, Wells T. Word and nonword repetition within- and across-modality: An event-related potential study. *Journal of Cognitive Neuroscience*. 1995; 7:209–227. doi:10.1162/jocn.1995.7.2.209. [PubMed: 23961825]
- Schoonbaert S, Grainger J. Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language and Cognitive Processes*. 2004; 19:333–367. doi: 10.1080/01690960344000198.
- Schutter DJLG, Leitner C, Kenemans JL, van Honk J. Electrophysiological correlates of cortico-subcortical interaction: A cross-frequency spectral EEG analysis. *Clinical Neurophysiology*. 2006; 117:381–387. doi:10.1016/j.clinph.2005.09.021. [PubMed: 16371254]
- Thorpe SJ, Fize D, Marlot C. Speed of processing in the human visual system. *Nature*. 1996; 381:520–522. doi:10.1038/381520a. [PubMed: 8632824]
- Whitney C. How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review*. 2001; 8:221–243. doi:10.3758/BF03196158. [PubMed: 11495111]
- Ziegler JC, Bertrand D, Lété B, Grainger J. Orthographic and phonological contributions to reading development: Tracking developmental trajectories using masked priming. *Developmental Psychology*. Advance online publication. 2013 doi: 10.1037/a0035187.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Table 1

Mean Correct RT and Percentage of Correct Lexical Decisions for Word and Nonword Stimuli Across Experimental Conditions

Word Stimuli							
Primes		Transposition			Substitution		
		Mean	Std. Error Mean	% Correct	Mean	Std. Error Mean	% Correct
Distance	Adjacent	521	20.0	.98	558	19.01	.93
	Non-adjacent	533	20.3	.96	550	18.0	.93
Nonword Stimuli							
Primes		Transposition			Substitution		
		Mean	Std. Error Mean	% Correct	Mean	Std. Error Mean	% Correct
Distance	Adjacent	629	20.1	.95	651	24.5	.94
	Non-adjacent	640	22.0	.95	640	23.7	.95