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There is no clam with coats in the calm coast: Delimiting the transposed-letter priming effect

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There is no *clam* with *coats* in the *calm coast*: Delimiting the transposed-letter priming effect

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In this article, we explore the transposed-letter priming effect (e.g., ju**gd**e–JU**DG**E vs. ju**pt**e–JUDGE), a phenomenon that taps into some key issues on how the brain encodes letter positions and has favoured the creation of new input coding schemes. However, almost all the empirical evidence from transposed-letter priming experiments comes from nonword primes (e.g., ju**gd**e–JU**DG**E). Indeed, previous evidence when using word–word pairs (e.g., ca**us**al–CA**SU**AL) is not conclusive. Here, we conducted five masked priming lexical decision experiments that examined the relationship between pairs of real words that differed only in the transposition of two of their letters (e.g., CA**SU**AL vs. CA**US**AL). Results showed that, unlike transposed-letter nonwords, transposed-letter words do not seem to affect the identification time of their transposed-letter mates. Thus, prime lexicality is a key factor that modulates the magnitude of transposed-letter priming effects. These results are interpreted under the assumption of the existence of lateral inhibition processes occurring within the lexical level—which cancels out any orthographic facilitation due to the overlapping letters. We examine the implications of these findings for models of visual-word recognition.

Keywords: Transposed-letter effect; Priming; Lexicality; Letter position assignment; Orthographic encoding.

When reading in an alphabetic language, we do not process *wrods* as a *wlohe* (see Grainger & Whitney, 2004). Instead, words are processed via their constituent letters. This implies that the visual-orthographic analyser in the brain needs to assess not only a word's letter identity, but also the relative position of the constituent letters. The issue of how letters are encoded forming meaningful strings is a crucial question for any computational model of visual-word recognition (Davis &

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Bowers, 2006; Grainger, 2008) and is currently generating a great deal of attention (e.g., Duñabeitia, Perea, & Carreiras, 2007; Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006a; Guerrera & Forster, 2008; Perea & Carreiras, 2006a, 2006b, 2006c; Perea & Lupker, 2004; Rayner, White, Johnson, & Liversedge, 2006; Velan & Frost, 2007; White, Johnson, Liversedge, & Rayner, 2008; Whitney, 2008b).

To examine letter position encoding, researchers have typically employed transposed-letter stimuli. A pair of transposed-letter "neighbours" is formed by two strings that share the same letters, and two of the letters are transposed (e.g., *TRIAL–TRAIL, COAST–COATS*, or *CLAM–CALM*). Because of linguistic restrictions—the number of transposed-letter word pairs tends to be rather small—most experiments have employed transposed-letter nonwords (e.g., *jugde*; the base word would be *judge*). There is substantial empirical evidence, obtained from different paradigms, that shows that transposed-letter *nonwords* tend to be misperceived as their corresponding base words (*jugde* being read as *judge*; Chambers, 1979; O'Connor & Forster, 1981; Perea & Carreiras, 2006c; Perea & Estévez, 2008; Perea & Fraga, 2006; Perea, Rosa, & Gómez, 2005).

More important for the present purposes, when the relationship between the transposed-letter nonwords and their corresponding base words is tested via a masked priming procedure (see Forster, Davis, Schoknecht, & Carter, 1987), there is a facilitative transposed-letter priming effect relative to an orthographic control (e.g., *jugde–JUDGE* vs. *jupte–JUDGE*; Christianson, Johnson, & Rayner, 2005; Duñabeitia et al., 2007; Perea & Carreiras, 2006c, 2008; Perea & Lupker, 2003a, 2003b; see also Carreiras, Vergara, & Perea, 2009; Duñabeitia, Molinaro, Laka, Estévez, & Carreiras, in press; Grainger, Kiyonaga, & Holcomb, 2006b, for ERP evidence; see also Johnson, Perea, & Rayner, 2007, for eye-movement evidence with parafoveal previews). The transposed-letter priming effect occurs not only for adjacent letter transpositions, but also for nonadjacent letter transpositions (e.g., *caniso–CASINO* vs. *caviro–CASINO*; Perea & Lupker, 2004; see also Lupker, Perea, & Davis, 2008; Perea & Carreiras, 2006a, 2008; Perea, Duñabeitia, & Carreiras, 2008b). In sum, the transposed-letter priming effect with nonword stimuli is a solid and well-documented phenomenon.

The robustness of transposed-letter effects has posed a serious challenge for position-specific ("slot") orthographic coding schemes (Hunter & Brysbaert, 2008), such as the interactive activation model (McClelland & Rumelhart, 1981), the multiple read-out model (Grainger & Jacobs, 1996), the dual-route cascaded model (Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001), or the CDP + model (Perry, Ziegler, & Zorzi, 2007): In these models, the nonwords *jupbe* and *jugde* should exert the same influence on *JUDGE* because these nonwords share with the target only three letters in the same position. Instead, the empirical evidence from transposed-letter nonwords favours more flexible models of encoding letter position such as the SOLAR model (Davis, 1999), the SERIOL model (Whitney, 2001, 2008a), the open-bigram model (Grainger & van Heuven, 2003), and the overlap model (Gómez, Ratcliff, & Perea, 2008).

What we should also stress here is that the rebuttal of "slot" coding schemes is mainly based on experiments using nonword stimuli—either in a single-presentation paradigm (e.g., is *jugde* a word?) or in priming paradigms with nonword primes (e.g., comparing *jugde–JUDGE* vs. *jupte–JUDGE*). Although models of visual-word recognition need to account for the reading of novel strings of letters, their main focus should be word stimuli. At an intuitive level, we may frequently experience reading *satl* as *salt*, but it may not be so common to misread *trial* with *trail*. The reason is that a transposed-letter nonword (e.g., *satl*) does not have an orthographic representation in the internal lexicon, and hence it may be easily attracted to a more stable representation (i.e., *salt*). In contrast, a word with a transposed-letter neighbour (e.g., *trial*) has its own lexical representation, and this may prevent *trial* from activating *trail* to a large degree. Given that lexicality seems to play a role in modulating transposed-letter effects (see Gómez et al., 2008, for evidence in a forced-choice identification task), it is important to examine the presence of transposed-letter priming effects with word stimuli (e.g., *SLAT* and *SALT*, *CLAM* and *CALM*, or *TRIAL* and *TRAIL*).

The empirical evidence of transposed-letter priming effects with word primes is very scarce. Andrews (1996) employed a masked priming paradigm with a naming task in which a transposed-letter word (*SALT*) could be preceded by its transposed-letter partner (*slat*), by an orthographic nonword neighbour created by replacing one of the original letters by another (*saft*), or by an unrelated word prime that resembled the target only in the first letter (*spin*). She found that responses times were 14 ms longer when the target word was preceded by a transposed-letter prime than when the target word was preceded by an unrelated prime—the effect did not approach significance in the item analysis ($p > .28$), though. Consistent with the general pattern of the latency data, the proportion of errors was higher in the transposed-letter priming condition than in the unrelated condition. Andrews interpreted her findings in terms of a mutual interference so that "both members of a transposed-letter pair are activated when a single transposed-letter word is presented" (pp. 785–786). More recently, Castles, Davis, and Forster (2003) reported a lexical decision experiment that explored masked transposed-letter priming effects for word pairs such as *sign–SING* relative to an unrelated condition (e.g., *clap–SING*) and failed to find a transposed-letter priming effect. Interestingly, Castles et al. also conducted the experiment with 3rd- and 5th-grade children, and they only obtained a (facilitative) transposed-letter priming effect with word pairs for beginning (3rd-grade) readers; note, however, that there was a high percentage of errors on the target items (around 32%), and this makes these data difficult to interpret (see Castles, Davis, Cavalot, & Forster, 2007). Thus, the evidence of a transposed-letter priming effect with word primes is not conclusive. Given the importance of this issue for models of visual-word recognition, the present study is aimed at studying in depth the interaction between prime lexicality and the transposed-letter priming effect.

The main goal of the present study is to investigate the relationships between transposed-letter word "neighbours" (e.g., *CAUSAL–CASUAL*) in visual-word recognition. To that end, participants in the experiments were presented with transposed-letter words and their transposed-letter word mates—we used different control conditions varying from single-substitution-letter controls (e.g., *CAUDAL*, flow) to double-substitution-letter controls (e.g., *CARNAL*, carnal) and completely unrelated words in a masked priming paradigm. The experiments were conducted in Spanish—note that previous research has shown a very similar pattern of masked transposed-letter priming effects in languages as different as Spanish, English, French, Basque, and Japanese (e.g., see Lupker et al., 2008; Perea & Carreiras, 2006a; Perea & Lupker, 2004; Perea & Pérez, 2009; Schoonbaert & Grainger, 2004). In the present series of experiments, we employed nonword foils that were pronounceable and orthographically legal in Spanish (e.g., *JOLAPE*), but they tended not to resemble any existing Spanish words. This way we minimized the chances that the priming effects were due to any potential task-specific checking processes that may occur when the nonword foils are too close to existing lexical representations (see Forster & Veres, 1998).

EXPERIMENTS 1A AND 1B

Prior research has shown that transposed-letter nonword primes facilitate the processing of their corresponding base words in a masked priming paradigm in relation to a double-letter substitution control priming condition (e.g., *jugde–JUDGE* vs. *jupte–JUDGE*; e.g., Perea & Lupker, 2003a, 2004; see also Duñabeitia et al., 2007; Perea & Carreiras, 2006a, 2006c). In Experiment 1, we simultaneously examined the transposed-letter priming effect for both word–word pairs and nonword–word pairs. To do this, we conducted two subexperiments. In Experiment 1a, we selected a group of transposed-letter (TL) word–word pairs in which the target word could be preceded by a transposed-letter high-frequency word prime (*cerdo–CEDRO*) or by a double-substitution word prime (*censo–CEDRO*). The idea here is that the high-frequency transposed-letter neighbour of a word may interfere with target recognition (*cerdo–CEDRO*), as actually happens when using substitution neighbours (see Davis & Lupker, 2006; Segui & Grainger, 1990). In Experiment 1b, we selected a group of Spanish nonword–word pairs, in which the target word could be preceded by a transposed-letter nonword prime (*cetla–CELTA*) or by a double-substitution nonword prime (*cefba–CELTA*). None of the target words in Experiment 1b had any transposed-letter neighbours. In Experiment 1b, we expected to replicate the facilitative transposed-letter priming effect that has been consistently obtained in the literature.

Thus, the critical issue was whether there is an inhibitory relatedness effect (or a reduced facilitation) from word TL-neighbours (as compared to the facilitative effect from nonword TL-neighbours)—this would be consistent with an increased lateral inhibition from transposed-letter word neighbours within the lexical level. What we should note here is that Forster and colleagues (e.g., Forster, 1987; Forster & Veres, 1998) were the first to examine the role of prime lexicality effect in masked priming—using substitution-letter primes.

Method

Participants

A total of 32 Spanish students from the University of La Laguna received course credit for participating in Experiments 1a and 1b. All of them had either normal or corrected-to-normal vision and were native speakers of Spanish.

Materials

For Experiment 1a (word–word pairs), we selected a set of 36 Spanish words. The mean frequency of these words was of 3.72 appearances per million (range: 0.18–34.29), and their mean length was 5.69 (range: 4–8). All these words had a higher frequency transposed-letter neighbour, and the mean number of substitution neighbours was 2.94 (range: 0–9). These words were preceded by Spanish prime words that were (a) the higher frequency neighbour by transposition (*cerdo–CEDRO*, "pig"–"CEDAR"), or (b) a double-substitution word in which the two critical letters were substituted by other letters (*censo–CEDRO*, "census"–"CEDAR"). All the prime words had higher lexical frequency than their corresponding target words (transposed-letter primes: mean = 23.33, range = 0.36–136.79; substituted-letter primes: mean = 24.85, range = 0.18–209.64), and none of the letter transposition involved letters across morphemes (Christianson et al., 2005; Duñabeitia et al., 2007).

For Experiment 1b (nonword–word pairs), we selected a set of 36 Spanish words. These words were matched to the target words in Experiment 1a in word frequency (mean: 3.67, range: 0.18–33.75), length (mean: 5.69, range: 4–8) and number of substitution neighbours (mean: 2.66, range: 0–14). These target words did not have any transposed-letter neighbours. The target words were preceded by nonword primes that were (a) the same as the target except for the transposition of two letters (*cetla–CELTA*; *CELTA* is the Spanish for "celtic"), or that were(b) the same as the target except for the substitution of the two letters involved in the transposition (*cefba–CELTA*). None of the letter transposition involved letters across morphemes. A set of 72 nonwords (mean Coltheart's *N*: 0.43, range: 0–5) was created for the purposes of the lexical decision task, paired to the target words in length (mean: 5.61, range: 4–8). The manipulation of the nonword trials was the same as that for the word trials (i.e., a transposed-letter prime vs. an unrelated prime). Two lists of materials were constructed so that each target appeared once in each list, but each time in a different priming condition (transposed letter or replacement letter). Different groups of participants were used for each list.

Procedure

Participants were tested individually in a quiet, well-lit room. Presentation of the stimuli and recording of response times were carried out using DMDX (Forster & Forster, 2003). The experimental trials began with the centred presentation of a forward mask of hash marks (#), followed by a 66-ms presentation of the lower-case prime and the immediate appearance of the upper-case target. We chose a 66-ms stimulus onset asynchrony (SOA) because recent studies contrasting theories of letter position coding have used this prime exposure (e.g., Davis & Bowers, 2006; Duñabeitia et al., 2007; Grainger & Jacobs, 1996; Grainger et al., 2006a; Schoonbaert & Grainger, 2004). Stimuli were presented in 12-pt Courier New font. Participants had to press one of two labelled keys, to determine whether the target string formed a legal word ("M" for yes and "Z" for no). They were instructed to make these decisions as fast and as accurately as possible. They were not informed of the presence of lower-case items. Each participant received a different order of trials. Each participant received a total of 10 practice trials prior to the experimental trials. The whole experiment lasted less than 5 minutes. None of the participants reported conscious knowledge of the existence of prime words when asked after the experiment.

Results and discussion

Incorrect responses (6.6% and 6.0% of the data in Experiments 1a and 1b, respectively) and response time beyond the 250–1,500-ms cut-off values (3.5%) were excluded from the latency data. The mean latencies for correct responses and error rates are presented in Table 1. For each subexperiment, analyses of variance (ANOVAs) based on the participant and item response latencies and error percentage were conducted based on a 2 (prime–target relatedness: transposed-letter, replaced-letter) × 2 (list: List 1, List 2) design. Prime–target relatedness was a within-subject factor, and list was a between-subjects factor. List was included as a dummy variable to extract the variance due to the counterbalancing lists (Pollatsek & Well, 1995).

Experiment 1a (word–word pairs)

Word data. None of the effects were significant (all Fs < 1).

Nonword data. None of the effects were significant (all ps $> .25$).

Experiment 1b (nonword–word pairs)

Word data. Words preceded by a transposed-letter nonword prime were responded to 28 ms faster than words preceded by a double-substitution nonword prime, $F_1(1, 30) = 5.16$, $p < .04$, $MSE = 2{,}440$; $F_2(1, 32) = 4.50$, $p < .05$.

The ANOVA on the error data did not show any significant effects (all ps $> .14$).

Nonword data. None of the effects were significant (all ps $> .25$).

The present experiment replicated the transposed-letter priming effect with nonword primes: The transposed-letter nonword *cetla* speeded the recognition of the word *CELTA* more than the

Table 1. *Mean lexical decision times and percentage of errors for word and nonword targets in Experiments 1 and 2*

			Type of prime		
		Trials	*Transposed letter*	*Replaced letter*	*Priming*
Experiment 1	a	Word–word trials	824 (9.4)	816 (9.0)	−8 (−0.4)
		Nonword–nonword trials	873 (5.9)	864 (6.8)	−9 (0.9)
	b	Nonword–word trials	773 (8.5)	801 (6.6)	28 (−1.9)
		Nonword–nonword trials	866 (5.2)	863 (5.0)	−3 (−0.2)
Experiment 2		Nonword–word trials (from 1a)	747 (9.0)	765 (11.1)	18 (2.1)
		Nonword–word trials (from 1b)	733 (10.2)	760 (10.4)	27 (0.2)
		Nonword–nonword trials	790 (6.4)	785 (7.1)	−5 (0.7)

Note: Mean lexical decision times in ms; percentages of errors in parentheses.

double-substitution nonword *cefba* did (e.g., Perea & Lupker, 2003a; see also Duñabeitia et al., 2007; Perea & Carreiras, 2006a). In contrast, there were no signs of a transposed-letter priming effect when using word primes (see Castles et al., 2003, for a similar failure to obtain a transposed-letter priming effect with word primes).

Thus, the lexicality of the prime appears to be a determining factor for the transposed-letter priming effect. But before reaching this conclusion, it is important to show that the null effect obtained with the transposed-letter word primes in Experiment 1a was not due to the (potential) peculiarities of the selected words. To examine this possibility, in Experiment 2 we employed the same transposed-letter words as those in Experiment 1a, except that we created transposed-letter (and double-substitution) nonword primes instead of transposed-letter (and double-substitution) word primes. That is, we used nonword–word pairs such as *cdero–CEDRO* and *cbaro–CEDRO*, instead of word–word pairs like *cerdo–CEDRO* and *censo–CEDRO*.

EXPERIMENT 2

Method

Participants

A total of 26 undergraduate Spanish students from the Universidad de La Laguna received course credit for participating in the experiment. All of them had either normal or corrected-to-normal vision and were native speakers of Spanish. None of them had taken part in Experiment 1.

Materials

We selected the same sets of 36 + 36 words as those from Experiment 1. Half of these words had a transposed-letter neighbour, whereas the other half had not. The only difference was that in the Experiment 2, the primes were always nonwords. Therefore, the 72 target words were preceded by primes that were (a) the same as the target except for a transposition of two letters (*cdero–CEDRO*), resulting in orthographically related transposed-letter nonwords, and (b) the same as the target except for the substitution of the two transposed letters by two form-related letters (*cbaro–CEDRO*). We also included the same set of 72 nonword targets as that used in Experiment 1, with their corresponding transposed-letter and double-substitution letter primes. Two lists of materials were constructed so that each target appeared once in each list, but each time in a different priming condition (transposed-letter neighbour or unrelated). Different groups of participants were used for each list.

Procedure

This was the same as that in Experiment 1.

Results and discussion

Incorrect responses (9.2% of the trials) and response times beyond 250–1,500 ms (2.7% of the data) were excluded from the latency analyses. The mean response times and error rates related to each experimental condition are presented in Table 1. ANOVAs based on the participant and item response latencies and error percentage were conducted based on a 2 (type of targets: words with transposed-letter neighbours, words without transposed-letter neighbours) × 2 (type of prime: transposed letter, replaced letter) × 2 (list: 1, 2) design.[1]

Word data. The results showed that words preceded by a transposed-letter nonword prime were recognized faster than words preceded by a double-substitution nonword prime (23 ms), $F_1(1, 24) = 11.65$, $p < .01$, $MSE = 1{,}175$; $F_2(1, 66) = 3.07$, $p = .08$, $MSE = 2{,}989$.[2] No differences were

[1] Two of the words from the nonword-primed set were discarded from the analyses because their error rates were higher than 50%. These words were *CAMPA* (a variety of "field") and *UNÍVOCO* ("univocal").

[2] One target word from the present experiment (i.e., *arce*, "maple tree") produced error rates higher than 60%. When this word was taken out from the analyses, the *p* value of the *F*2 analysis was reduced to .04.

found between the subgroups of target words, both Fs < 1. The interaction between the two factors was not significant, showing that the transposed-letter effect occurred similarly for words with and without transposed-letter neighbours, both Fs < 1. The ANOVA on the error data did not reveal any effects that approached significance (all ps > .3).

Nonword data. None of the effects were significant (all Fs < 1).

The present results have shown a transposed-letter priming effect (around 18 ms) when the target words from Experiment 1 were preceded by a nonword prime. Thus, the null effect for word–word pairs in Experiment 1 was not due to the nature of the selected words: When these same words are preceded by a nonword prime, the transposed-letter priming effect has been reinstated. Thus, it seems that the lexicality of the prime and not the characteristics of the set of stimuli is the factor responsible for the absence/presence of the transposed-letter priming effect.

One might argue that the control condition for the word primes in Experiment 1a could have been (in part) responsible for the null effect of priming—note that the control prime for the pair *cerdo–CERDO* was a double-substitution prime (*censo–CEDRO*). When using higher frequency substitution neighbours as primes, high-frequency substitution neighbours of a word (*coat*) interfere with target recognition (*CHAT*) relative to an unrelated prime (*tree*; see Davis & Lupker, 2006; Segui & Grainger, 1990). In Experiment 3, we investigated whether transposed-letter neighbours behave as substitution neighbours, by using unrelated word primes as controls. Specifically, a target word (*CEDRO*) was preceded by its higher frequency transposed-letter mate (*cerdo*) or by an unrelated word prime of a similar frequency to the related prime (*botón*). If transposed-letter neighbours do behave as substitution neighbours, we expected an inhibitory relatedness effect (Davis & Lupker, 2006; Segui & Grainger, 1990; see also Carreiras & Perea, 2002).

EXPERIMENT 3

Method

Participants

A total of 40 undergraduate students from the University of La Laguna received course credit for participating in the experiment. All of them had either normal or corrected-to-normal vision and were native speakers of Spanish. None of the participants had taken part in the previous experiments.

Materials

We selected a set of 42 Spanish target words. The mean frequency of these words was of 8.70 per million (range: 0.18–65; from the Sebastián-Gallés, Martí, Carreiras, & Cuetos, 2000, LEXESP database). The mean length was 5.5 letters (range: 4–9), and the mean number of substitution neighbours was 3.52 (range: 0–19; from the Davis & Perea, 2005, B-Pal software). The target words were presented in upper case and could be preceded by words in lower case that were: (a) a higher frequency transposed-letter neighbour (*cerdo–CEDRO*, "pig"–"CEDAR"), or (b) an unrelated word (*botón–CEDRO*, "button"–"CEDAR"). The transposed-letter and unrelated primes had always a higher word frequency than the corresponding target words (mean frequency: 85 vs. 81, respectively; mean N: 4.8 vs. 4.3, respectively). An additional set of 42 legal (pronounceable) nonwords was created for the purposes of the lexical decision task. The target nonwords were matched to the target words in length (mean: 5.47, range: 4–7) and neighbourhood size (mean N: 0.83, range: 0–5). The manipulation of the pseudoword trials was the same as that for the word trials (i.e., a transposed-letter prime vs. an unrelated prime). Two lists of materials were constructed so that each target appeared once in each list, but each time in a different priming condition (transposed-letter neighbour or unrelated). Different groups of participants made up each list.

Procedure
This was the same as that in Experiment 1.

Results and discussion

Incorrect responses (5.5% of the trials) and response times beyond the 250–1,500-ms cut-off points (5.2% of the data) were excluded from the latency analyses. The mean latencies for correct responses and error rates are presented in Table 2. Mixed ANOVAs based on the participant and item response latencies and error percentage were conducted based on a 2 (prime–target relatedness: transposed-letter prime, unrelated) × 2 (list: List 1, List 2) design. List was included as a dummy between-subjects factor.

Word data. The ANOVA on the latency data did not reveal any differences between the words preceded by transposed-letter primes and those preceded by unrelated primes, $F_1(1, 38) = 0.01$, $p > .92$, $MSE = 1{,}092$; $F_2(1, 40) = 0.21$, $p > .64$, $MSE = 2{,}729$. The ANOVA on the error data did not reveal an effect of relatedness, $F_1(1, 38) = 1.56$, $p > .21$, $MSE = 35$; $F_2(1, 40) = 1.88$, $p > .17$, $MSE = 31$.

Nonword data. The ANOVA on the response times did not show a significant effect of relatedness, $F_1(1, 38) = 0.23$, $p > .63$, $MSE = 1{,}832$; $F_2(1, 40) = 1.41$, $p > .24$, $MSE = 1{,}992$. The ANOVA on the error data revealed that participants made fewer errors to nonwords preceded by transposed-letter primes than to nonwords preceded by unrelated primes, $F_1(1, 38) = 4.93$, $p < .04$, $MSE = 10$; $F_2(1, 40) = 4.88$, $p < .04$, $MSE = 10$.

The outcome of the experiment is clear: Again, we found no signs of inhibition in the processing of a target word when the prime was a high-frequency transposed-letter neighbour relative to an unrelated word prime (*cerdo–CEDRO* vs. *botón–CEDRO*). Unlike the usual inhibitory priming effect with higher frequency word primes obtained with substitution neighbours (e.g., Segui & Grainger, 1990) or syllabic neighbours (Carreiras & Perea, 2002), we failed to obtain any signs of a parallel effect with transposed-letter neighbours. (We found a small, but significant, effect of transposed-letter priming on the error data for nonwords, 1.6%; however, masked priming effects for nonwords in lexical decision do not tend to be reliable—probably because they may depend on the participant's strategies when making "no" responses; see Perea et al., 2005.)

Thus, the interim conclusion is that transposed-letter neighbours do not behave exactly as substitution neighbours. But, again, before reaching this conclusion, it is important to show that the lack of an inhibitory effect in Experiment 3 is not due to special characteristics of the selected target words, but to the relationship between primes and targets. If this were the case, an inhibitory relatedness effect should show up when the same words are preceded by higher frequency substitution neighbours (see Bijeljac-Babic, Biardeau, & Grainger, 1997; Ferrand & Grainger, 1996; Segui & Grainger, 1990). This is the goal of Experiment 4.

Table 2. *Mean lexical decision times and percentages of errors for word and nonword targets in Experiment 3*

	Type of prime		
Experiment 3	*Transposed letter*	*Unrelated*	*Priming*
Word–word trials	774 (9.0)	774 (7.4)	0 (−1.6)
Nonword–nonword trials	857 (2.1)	862 (3.7)	5 (1.6)
18 word–word trials (Exp. 4)	746 (5.5)	739 (4.2)	−7 (−1.3)

Note: Mean lexical decision times in ms; percentages of errors in parentheses.

EXPERIMENT 4

The manipulation in Experiment 4 was exactly the same as that in Experiment 3, except that the related primes were higher frequency substitution neighbours instead of higher frequency transposed-letter neighbours.

Method

Participants

A total of 28 students from University of La Laguna received course credit for participating in the experiment. All of them had either normal or corrected-to-normal vision and were native speakers of Spanish. None of them had taken part in the previous experiments.

Materials

We selected only those target words from Experiment 3 that had a higher frequency substitution neighbour. A total of 18 words fulfilled this criterion. A post hoc analysis over these items in Experiment 3 showed no effects of transposed-letter priming (see Table 3). The 18 words had a mean frequency of 4.43 (range: 0.36–16.43) and a mean number of 5.1 letters (range: 4–7). The mean frequency of the higher frequency substitution neighbour was 31.79 per million. We also created a set of 18 unrelated word primes of the same length as the related primes (mean frequency: 30.60). Thus, each target word (e.g., *CAUSAL*) could be preceded by its higher frequency substitution neighbour (e.g., *caudal*, "flow") or by an unrelated word (e.g., *toalla*, "towel"). A set of 18 orthographically legal nonwords was also created for the purposes of the lexical decision task (mean Coltheart's *N*: 0.89; range: 0–5; mean length = 5.14, range: 4–7). The manipulation of the nonword trials was the same as that for the word trials.

Procedure

This was the same as that in Experiment 1.

Table 3. *Mean lexical decision times and percentages of errors for word and nonword targets in Experiment 4*

	Type of prime		
Experiment 4	*Substitution letter*	*Unrelated*	*Priming*
Word–word trials	706 (5.6)	687 (6.0)	−19 (0.4)
Nonword–nonword trials	779 (6.3)	782 (5.2)	3 (−1.1)

Note: Mean lexical decision times in ms; percentages of errors in parentheses.

Results and discussion

Incorrect responses (5.7% of the word data) and responses with latencies beyond the 250–1,500-ms cut-off points (1% of the word data) were excluded from the latency analyses. Mean reaction times and percentages of errors are presented in Table 3. ANOVAs based on the participant and item response latencies and error percentage were conducted based on a 2 (prime–target relatedness: higher frequency substitution neighbour, unrelated) × 2 (list: List 1, List 2) design.

Word data. Participants responded 19 ms more slowly to words preceded by a higher frequency substitution neighbour than to words preceded by an unrelated word, $F_1(1, 26) = 4.96$, $p < .04$, $MSE = 1{,}008$; $F_2(1, 16) = 5.24$, $p < .04$, $MSE = 695$. The ANOVA on the error rates did not show any significant difference (both Fs < 1).

Nonword data. None of the effects were significant (all ps > .15).

By using a subset of words from Experiment 3, we replicated the inhibitory relatedness effect from higher frequency substitution neighbours (*caudal–CAUSAL* vs. *toalla–CAUSAL*). Besides adding empirical evidence in favour of inhibition from higher frequency substitution neighbours (Segui & Grainger, 1990; see also Bijeljac-Babic et al., 1997; Davis & Lupker, 2006), this finding confirms that the null transposed-letter priming effect in Experiment 3 is not due to the specific words that were selected, or the characteristics of the task, but rather to the relationship between primes and targets. Therefore, it seems that transposed-letter neighbours like *CASUAL* and *CAUSAL* are not related in exactly the same way as substitution neighbours like *CAUDAL* and *CAUSAL*.

EXPERIMENTS 5A AND 5B

The results from the previous sets of experiments do not show any signs of coactivation of the two members of a transposed-letter word pair. It should be noted that in Experiments 3–4, all prime words were of higher frequency than the target words. In Andrews's (1996) masked priming experiment, the two members of the transposed-letter pair were presented twice (in different blocks), so that the low-frequency member acted as a prime or as a target, depending on the block. Andrews found that, irrespective of the frequency manipulation, words preceded by a transposed-letter word prime were recognized more slowly and less accurately than words preceded by an unrelated prime—note, however, that the transposed-letter priming effect was not significant in the item analyses.

In Experiment 5, and in a new attempt to examine the presence of transposed-letter priming effect with word–word pairs, we examined whether a high-frequency transposed-letter word could be influenced by its lower frequency transposed-letter mate. Note, however, that Segui and Grainger (1990), using substitution neighbours, did not find any signs of a priming effect when high-frequency target words were preceded by lower frequency substitution neighbours (relative to an unrelated word priming condition; but see Nakayama, Sears, & Lupker, 2008).

In Andrews's (1996) priming experiment, the SOA employed was 56 ms. Although the SOA difference regarding our previous experiments is small (10 ms) and, on a priori grounds, should not be the reason for the divergent results, we wished to examine whether this potential difference played a role in the size of the priming effects. For that reason, Experiment 5 was conducted using two different samples of participants and two different SOAs: 50-ms SOA (Experiment 5a) and 66-ms SOA (Experiment 5b).

Method

Participants

A total of 50 students from the University of La Laguna received course credit for participating in these experiments. All of them had either normal or corrected-to-normal vision and were native speakers of Spanish. None of them had taken part in Experiments 1–4. A total of 26 participants took part in Experiment 5a, and 24 participants completed Experiment 5b.

Materials

We selected a set of 42 high-frequency Spanish words as targets—these words had been the related primes in Experiment 3. These target words could be preceded by their corresponding transposed-letter low-frequency neighbours (i.e., the target words in Experiment 3) or by an unrelated word. The unrelated word primes were matched as closely as possible to the related primes in word frequency (mean: 8.77) and number of substitution neighbours (mean: 3.4, range: 0–15). Thus, target words were preceded by primes that were (a) a transposed-letter neighbour from the target (*cedro–CERDO*, "cedar"–"PIG"), or (b) an unrelated word (*noria–CERDO*, "big wheel"–"PIG") All the targets had higher frequencies than their corresponding primes. The same set of nonword targets as that used in Experiment 3 was used in the present experiment. Two lists of materials were created for this experiment (following a counterbalanced design).

Procedure

The procedure for Experiment 5a was the same as that in Experiment 1. In Experiment 5b, the procedure was the same as that in Experiment 5a except that the SOA was set to 50 ms (instead of 66 ms).

Results and discussion

Incorrect responses (0.3% of the data in Experiment 5a and 4.2% in Experiment 5b) and reaction times that fell beyond the cut-off values of 250–1,500 ms (0.6% of the trials in Experiment 5a and 2.6% in Experiment 5b) were not included in the latency analyses. Mean response latencies and percentages of errors are presented in Table 4. ANOVAs based on the participant and item response latencies and error percentage were conducted based on a 2 (prime–target relationship: transposed-letter, unrelated) × 2 (list: List 1, List 2) design.

Experiment 5a

Word data. None of the effects were significant (all *F*s < 1).

Nonword data. None of the effects were significant (all *F*s < 1).

Experiment 5b

Word data. None of the effects were significant (all *F*s < 1).

Nonword data. Participants recognized faster the nonwords preceded by an orthographically related prime (transposed-letter primes) than the nonwords preceded by an unrelated prime (13 ms faster). However, this difference did not approach significance, $F_1(1, 26) = 1.38$, $p > .20$; $F_2(1, 40) = 1.62$, $p > .20$. The ANOVA on the error data did not reveal any significant effects (both ps > .20).

Again, there were no signs of a priming effect with transposed-letter word primes. Unlike Andrews's (1996) masked priming experiment, no signs of an inhibition effect were found when priming a transposed-letter word with its low-frequency transposed-letter mate relative to an unrelated prime. Indeed, the potential criticism that the SOA in Andrews's experiment was slightly shorter than that in our previous experiments (56 vs. 66 ms) does not apply here: The pattern of results was very much the same at the 66- and 50-ms SOAs. Thus, once more we failed to obtain a transposed-letter priming effect with word primes, and, furthermore, the argument of a potential interaction between the SOA and the magnitude of priming effects cannot be applied to our data.

GENERAL DISCUSSION

The main findings of the present series of masked priming experiments can be summarized as follows. First, transposed-letter word primes do not produce any signs of a priming effect when compared with an unrelated word condition (e.g., *causal–CASUAL* vs. *toalla–CASUAL*; Experiments 3–5). Second, the absence of a transposed-letter priming effect with word primes is irrespective of the prime/target relative frequency (Experiments 3–4). Third, there are no signs of a transposed-letter priming effect with word primes when the control condition is a double-substitution word (e.g., *causal–CASUAL* vs. *carnal–CASUAL*; Experiment 1). Fourth, there is a robust transposed-letter priming effect when the primes were nonwords (i.e., lexicality of the transposed-letter prime is a determining factor; Experiments 1–2)—note that the lack of a transposed-letter priming effect with word primes cannot be attributed to the characteristics of the target words employed in the experiment because the same set of materials replicates other well-established masked priming effects: an inhibitory effect from higher frequency substitution neighbours (Experiment 4), and a

Table 4. *Mean lexical decision times and percentage of errors for word and nonword targets in Experiment 5*

			Type of prime		
			Transposed letter	*Unrelated*	*Priming*
Experiment 5a	66-ms SOA	Word–word trials	689 (4.9)	686 (4.0)	−3 (−0.9)
		Nonword–nonword trials	693 (1.8)	697 (1.5)	4 (−0.3)
Experiment 5b	50-ms SOA	Word–word trials	684 (3.7)	678 (3.1)	−6 (−0.6)
		Nonword–nonword trials	739 (4.3)	752 (5.8)	13 (1.5)

Note: Mean lexical decision times in ms; percentages of errors in parentheses.

facilitative transposed-letter priming effect from nonword primes (Experiment 2). Taken together, the present findings have important implications for models of visual-word recognition.

As indicated in the Introduction, the strongest evidence in favour from a significant transposed-letter priming effect with word stimuli comes from the study of Andrews (1996). Andrews reported that, under masked priming conditions, responses to words preceded by a transposed-letter word prime were slowed down relative to an unrelated control prime. (Note, however, that this difference was not significant in the analysis by items, $p > .28$.) Nonetheless, Castles et al. (2003) reported a failure to replicate the masked transposed-letter priming effect with word primes in a behavioural study. Furthermore, in a recent experiment, Duñabeitia et al. (in press) examined the electrophysiological correlates associated with transposed-letter word–word and nonword–word pairs in a masked priming semantic categorization task. Duñabeitia and colleagues found that words preceded by a replacement-letter nonword elicited a more negative-going waveform between 150–250 ms (characterized as the N250 component) for words preceded by a transposed-letter nonword, replicating preceding event-related potential (ERP) evidence (e.g., Grainger et al., 2006b). More importantly, the N250 effect *vanished* for word–word manipulations (e.g., *casual–CAUSAL* vs. *carnal–CAUSAL*). Taken together, the present findings strongly suggest that prime lexicality also has a clear impact on transposed-letter priming—importantly, masked priming effects with transposed-letter word neighbours (*trial–trail*) behave differently from priming effects with substitution-letter word neighbours (*train–trail*; see Davis & Lupker, 2006, for extensive discussion of priming effects with substitution-letter neighbours).

Indeed, the empirical evidence of an inhibitory effect with transposed-letter neighbours (e.g., longer response times to **trail**—because of the higher frequency neighbour **trial**, relative to a matched control word with no transposed-letter neighbours) in single-presentation experiments is also scarce.[3] For instance, Perea, Acha, and Fraga (2008a) failed to find an inhibitory effect from the higher frequency transposed-letter neighbours in a lexical decision task, whereas they found a significant inhibitory effect of neighbourhood frequency for addition/deletion neighbours. Furthermore, in a recent study in which the participant's eye movements were monitored, Acha and Perea (2008) found that the effect of transposed-letter neighbourhood was negligible in early pass measures (e.g., first-fixation durations, gaze durations), and it only appears on late measures such as the percentage of regressions back to the target word. That is, Acha and Perea found an effect of neighbourhood frequency for transposed-letter neighbours, but it occurred quite late in processing (see Johnson, 2008, for a remarkably similar pattern). Interestingly, research on substitution or on addition/deletion neighbours has reported an inhibitory effect from a word's higher frequency neighbours in earlier measures in normal silent reading (e.g., gaze durations; see Davis, Perea, & Acha, in press; Pollatsek, Perea, & Binder, 1999). Therefore, transposed-letter word neighbours do not seem to behave exactly as other types of "neighbours" (e.g., substitution neighbours, addition/deletion neighbours, or syllabic neighbours).

What are the implications of the present findings for models of visual-word recognition? Activation-based accounts of masked priming (inspired by the interactive activation model; McClelland & Rumelhart, 1981) predict a lexical inhibition process when word–word pairs are presented, because lexical competitors of the target would be strongly activated (Davis & Lupker, 2006, for extensive discussion). In contrast, when nonword–word pairs are presented, there would be preactivation of the word by the nonword prime, and hence the expected effect would be

[3] We must bear in mind that, in a priming paradigm, an item is explicitly activated, and the effect on target performance is measured. In contrast, in a single-presentation paradigm, the issue concerns whether partial activation of neighbouring words that were never presented influences responses to the target item.

facilitative because "nonwords are, by definition, not lexically represented" (Davis & Lupker, 2006, p. 668). Thus, one would predict a facilitative nonword–word transposed-letter priming effect (as actually happened) and an inhibitory word–word transposed-letter effect. This is actually the pattern of effects that occurs with substitution neighbours (Experiment 2; see also Perea & Rosa, 2000) and with syllabic neighbours (Carreiras & Perea, 2002). In the present set of experiments, we obtained a facilitative priming effect from transposed-letter nonword primes, but we failed to obtain an inhibitory effect from transposed-letter word primes. How can we explain the obtained pattern of results from an activation-based model? One possibility is that transposed-letter word pairs (e.g., *casual–causal*) will generate more orthographic activity—they share *all* the letters—than substitution-letter word pairs (e.g., *caudal–causal*), and hence lexical inhibition from the higher frequency word prime could be cancelled out by bottom-up activation resulting from orthographic overlap. Of course, simulations of an activation-based account (with an appropriate input coding scheme) are necessary to assess how the model can account simultaneously for an inhibitory effect of higher frequency substitution primes and a null effect of higher frequency transposed-letter primes.

In addition, activation-based models can, in principle, account for the presence of transposed-letter priming for nonword primes but not for word primes with some tweaking, considering as "neighbours" those words that are one letter different from others—that is, one would expect some lexical competition especially between addition, deletion, and substitution neighbours (Davis & Taft, 2005). The idea is that the lexical entries that are activated when a transposed-letter word is presented are those one-letter-different words from the prime (e.g., the prime word *slat* would activate *flat*, *seat*, *slot*, *slap*, and other substitution or addition/deletion neighbours from it; see Figure 1). In contrast, the lexical entries that are activated when a transposed-letter nonword is presented would be those words that constitute all the attractors for the letter string. Therefore, a transposed-letter nonword like *satl* would activate the word unit corresponding to *salt*. In contrast, the transposed-letter word slat is less likely to produce a high level of activation in salt—given that it was its own lexical representation (i.e., its own attractor in the lexical system).

There is an alternative account of the present findings. Forster's entry-opening model (Forster, 1987; Forster et al., 1987; Forster, Mohan, & Hector, 2003) is based on the "perfect match" hypothesis in masked priming. A masked prime activates, or opens, the lexical entries of several lexical candidates that are temporarily flagged. For those candidates to be selected, a verification process must occur, and this generally happens while reading the target word. Therefore, all the flagged candidates from the prime are helpful (facilitative) in the target recognition—at least when the neighbourhood density of the target is not high. The entry-opening model (as put forward by Forster & Veres, 1998) does not offer a ready explanation for the prime lexicality effect. One option to explain the presence of a null effect for transposed-letter word primes would be increasing the importance of the verification process, so that the probability of verifying the masked prime is increased. However, this account runs into difficulties when trying to (simultaneously) accommodate the inhibitory effect with higher frequency substitution word primes found in Experiment 5 (see also Davis & Lupker, 2006; Segui & Grainger, 1990).

What are the implications of the present data for the recently proposed input coding schemes for models of visual-word recognition? Recently proposed orthographic coding schemes such as the SOLAR model (Davis, 1999), the overlap model (Gómez et al., 2008), or the SERIOL model (Whitney, 2001) predict that a transposed-letter item is highly confusable with its transposed-letter word mate at an orthographic level (i.e., *casual* and *causal* would be perceptually similar). Clearly, these coding schemes readily capture the facilitative priming effects with transposed-letter nonword primes (see Perea & Lupker, 2004). With respect to the null priming effect with word primes, the most plausible explanation is the

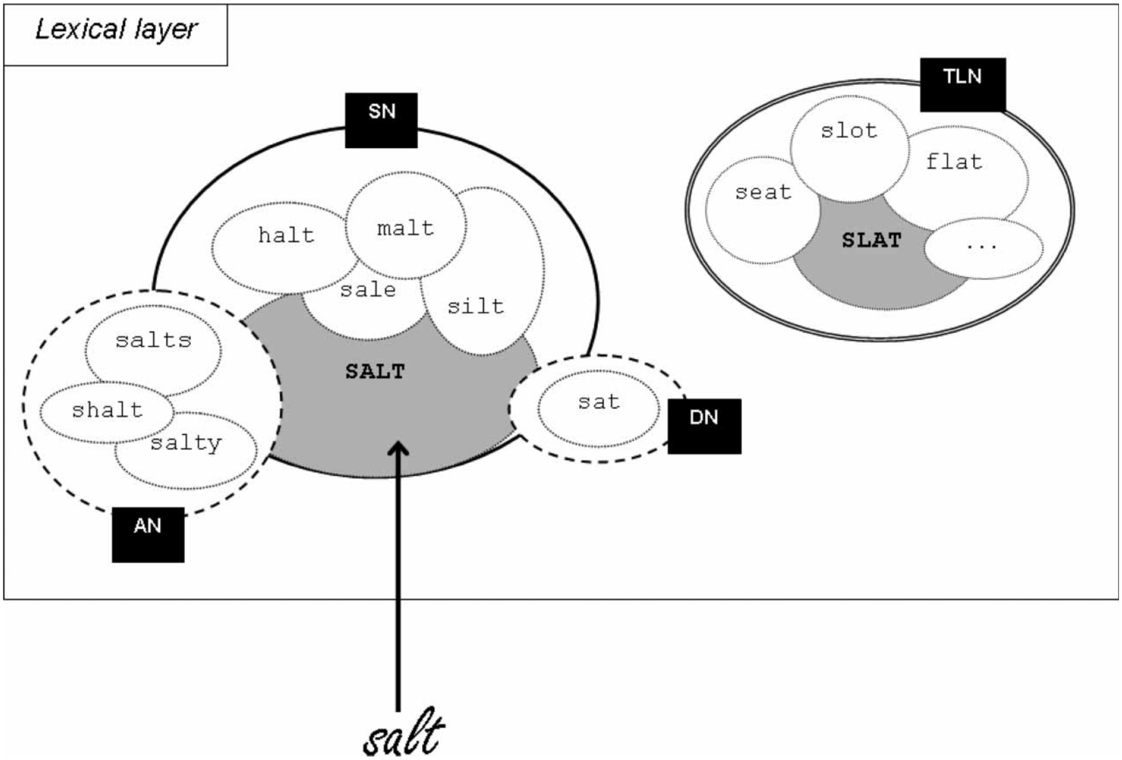

Figure 1. *The organization of the lexical neighbourhood. SN refers to one-letter substitution neighbours; AN and DN refer to addition and deletion neighbours; TLN refers to transposed-letter neighbours. All adjacent circles would activate each other whereas nonadjacent circles would not.*

presence of lateral inhibition within the lexical level, which could reduce the impact of the orthographic facilitation. Of course, simulations on a specific implementation of these models are necessary to examine their predictions. For example, the SOLAR model (Davis, 1999) was able to account for Andrews's (1996) results. Simulations with the SOLAR model show an inhibitory effect from the lower frequency transposed-letter neighbours. In his simulations, Davis found that "TL [transposed-letter] similarity 'helps' low frequency words and 'hurts' high frequency words" (p. 319). However, we failed to find any signs of a transposed-letter priming effect for word primes, irrespectively of the relative prime/target frequency. Thus, the present results pose a problem for the current version of the SOLAR model, and some parameter tweaking will be necessary to account for the present findings. The SERIOL model (Whitney & Cornelissen, 2008)[4] also predicts that a transposed-letter prime should exert a higher activation on the target than would a double-substitution word/nonword prime. Even though this was the case in our study for the nonword–word pairs, Whitney and Lavidor (2005) stated that "having a transposed-letter neighbour can be inhibitory" (p. 208). That is, in the SERIOL model, the reduced facilitation from

[4] We compared the scores for transposed-letter pairs (e.g., *cerdo–CEDRO*) and double-substitution pairs (e.g., *censo–CEDRO*) using the Match Calculator software, Version 1.9, programmed by Colin J. Davis. This application is available at Colin Davis' website: http://www.pc.rhul.ac.uk/staff/c.davis/Utilities/MatchCalc/index.htm

lexical TL-neighbours (as compared to nonword TL-neighbours) would be explained by increased lateral inhibition within the lexical level. Again, specific simulations on this model are necessary to examine whether it can simultaneously accommodate the presence of a null effect of transposed-letter word primes and an inhibitory effect of substitution word primes. Finally, in the overlap model (Gomez et al., 2008), letters in the visual stimulus have distributions over positions so that the representation of one letter will extend into adjacent letter positions (i.e., a measure of "noise"). In the overlap model, the spread of the encoded letter positions is narrower and more precise for words than for nonwords; the rationale here is that top-down influences allow for the position uncertainty to be reduced faster when words are presented. Nonetheless, a fully implemented version of the overlap model is necessary to examine whether it can capture the whole pattern of data in the present experiments.

In summary, the present series of experiments has examined a key issue in visual-word recognition: how letter positions are attained in words. We have shown that the lexicality of the prime plays a key role in transposed-letter priming effects: It is easy to misperceive the nonword *JUGDE* with *JUDGE*, but not the word *CASUAL* with *CAUSAL*, at least under the experimental paradigm used here. Thus, a lexical transposed-letter prime provides substantially less facilitation (a null effect) than a nonword transposed-letter prime. As a final point, the presence of differential priming effects for substitution neighbours and transposed-letter neighbours constrains the choice of parameters in the computational models of visual-word recognition.

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