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Brief article

The effect of neighborhood frequency in reading: Evidence with transposed-letter neighbors ☆

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Abstract

Transposed-letter effects (e.g., jugde activates judge) pose serious models for models of visual-word recognition that use position-specific coding schemes. However, even though the evidence of transposed-letter effects with nonword stimuli is strong, the evidence for word stimuli is scarce and inconclusive. The present experiment examined the effect of neighborhood frequency during normal silent reading using transposed-letter neighbors (e.g., silver, sliver). Two sets of low-frequency words were created (equated in the number of substitution neighbors, word frequency, and number of letters), which were embedded in sentences. In one set, the target word had a higher frequency transposed-letter neighbor, and in the other set, the target word had no transposed-letter neighbors. An inhibitory effect of neighborhood frequency was observed in measures that reflect late processing in words (number of regressions back to the target word, and total time). We examine the implications of these findings for models of visual-word recognition and reading.

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1. Introduction

How the brain encodes letter identities/positions within a word has become a key issue for any model of visual-word recognition (Grainger, 2008). There is substantial empirical evidence, obtained from different paradigms, that shows that transposed-letter nonwords tend to be (initially) misperceived as their corresponding base words (*CHOLOCATE* being read as *CHOCOLATE*; see Christianson, Johnson, & Rayner, 2005; O'Connor and Forster, 1981; Perea & Lupker, 2003; Rayner, White, Johnson, & Liversedge, 2006; Schoonbaert & Grainger, 2004; Velan & Frost, 2007). The robustness of the transposed-letter effect poses a serious challenge for position-specific orthographic coding schemes, 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), and the CDP+ model (Perry, Ziegler, & Zorzi, 2007). Note that these models cannot predict any confusion between transposed-letter pairs: the nonwords *jupbe* and *jugde* should exert the same influence on *JUDGE* because these nonwords share three letters in the same position with the target.

In the past years, several input coding schemes have been proposed in which transposed-letter effects are a natural consequence of the letter encoding process (SOLAR model, Davis, 1999; open-bigram models, Grainger & Whitney, 2005). However, the rebuttal of position-specific coding schemes is essentially based on experiments using transposed-letter nonwords. Although models of visual word recognition need to account for the reading of novel strings of letters, their main focus should be the word stimuli (i.e., normal reading).

In the present study, we examine the role of a word's transposed-letter neighbors in normal silent reading. (Note that two words are transposed-letter neighbors when they share the same letters, but two letters are swapped; e.g., trial–trial or causal–casual) More specifically, we focus on whether the presence of a higher frequency transposed-letter neighbor slows down the processing of the target word relative to a control word that is matched on other variables but doesn't have higher-frequency transposed-letter neighbors – that is, a neighborhood frequency manipulation (see Grainger, O'Regan, Jacobs, & Segui, 1989). If the transposed-letter neighbor (e.g., silver) has a substantially higher frequency in the language than the word actually presented (e.g., sliver), it seems plausible that activation of this higher frequency neighbor could compete with the activation of the 'correct' lexical entry and produce inhibitory effects. Indeed, there is evidence of an inhibitory effect of "neighborhood frequency" in normal silent reading when using higher frequency substitution neighbors (e.g., spice because of space; Perea & Pollatsek, 1998; Pollatsek, Perea, & Binder, 1999; but see Sears, Sharp, & Lupker, 2006, for a partial replication).

Up to now, the evidence supporting the effects of transposed-letter for word stimuli is scarce and inconclusive. With the lexical decision task, Chambers (1979) found an inhibitory effect of transposed-letter neighborhood frequency for low-frequency words, but other studies failed to replicate the effect (Andrews, 1996; Perea, Acha, & Fraga, in press). Also in lexical decision, Andrews (1996) found a 32 ms disadvantage of high-frequency words with a lower frequency transposed-letter neighbor compared with matched controls with no transposed-letter neighbors (but see Duñabeitia, Perea, & Carreiras, submitted for publication, for a failure to replicate). Finally, in a naming task, Andrews (1996) found a much larger proportion of errors for low-frequency words with a higher frequency transposed-letter neighbor relative to their matched controls with no transposed-letter words (14.2 vs. 4.2% of errors, respectively); however Andrews' latency data failed to show an inhibitory neighborhood frequency effect.

It is not entirely clear to us why the pattern of transposed-letter effects is not clear for word stimuli. One possibility, raised by Andrews (1996) in reference to the lexical decision experiments, is that "lexical classification tasks may be an unreliable index of the impact of co-activation of similar lexical representations" (p. 784). Indeed, the 'yes' response in the lexical decision task to a word may not only being driven by lexical access of that particular word, but it also is likely to be driven by the global activation in the lexicon, as indicated in the multiple read out model (Grainger & Jacobs, 1996) and in the dual route cascaded model (Coltheart et al., 2001). Therefore, in a study investigating the effect of higher frequency transposed-letter neighbors, a participant may respond 'yes' to the activation of a word's higher frequency neighbor, to activation of the target word itself, or even to some degree of global activation in the lexicon. Thus, the best way to test whether there is competition among lexical entries is by making people encode words in context when reading for meaning (see Pollatsek et al., 1999): If a neighborhood frequency effect is found with transposed-letter word stimuli, then one has clear evidence that transposed-letter effects are not restricted to nonword stimuli and are actually influencing normal reading. Furthermore, the use of eye-movement techniques allows us to shed light on the time course of these effects, the reason being that the series of eye movements offers a sequential record of the processing of the text material.

We should also note that in prior silent normal reading experiments using substitution neighbors (e.g., Perea & Pollatsek, 1998; Pollatsek et al., 1999), the effect of neighborhood frequency tends to reflect late aspects of lexical processing (i.e., regressions back to the target word, total time), which indicates that words with higher frequency neighbors are more difficult to process. Notably, there are no early signs of processing difficulty on these words (e.g., effects of first fixation durations). This is consistent with the predictions of the E-Z Reader model of eye movement control (Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998). The E-Z reader model posits two stages of lexical access (named L1 and L2) that occur during the processing of a word in text. Complete lexical access is only accomplished when both stages are completed. As indicated by Williams, Perea, Pollatsek, and Rayner (2006), one might loosely associate L1 with an early activation stage in an activation-verification framework (Paap, Newsome, McDonald, & Schvaneveldt, 1982). The end of L1 is thought to be the point at which there is sufficient activation from all this lexical activity so that there is a high probability that L2 (i.e., complete lexical access) would be achieved before the eyes moved to the next word. In the "verification" stage, which loosely is related to L2, there is competition among the various lexical entries. This implies that word units that are highly activated (e.g., a high-frequency neighbor) may inhibit word recognition in this stage. The net result is that words with higher frequency competitors may induce some spillover effects (i.e., a longer duration of the first fixation after leaving the target word), a larger number of regressions back to the target word (e.g., some of the lexical entries may be misperceived in the first pass; see Pollatsek et al., 1999), and hence an increased total time, compared with matched control words. This is precisely the pattern found in previous research on the neighborhood frequency effect with substitution neighbors (Perea & Pollatsek, 1998; Pollatsek et al., 1999).

In sum, all the recently proposed models of visual-word recognition (e.g., SOLAR model, Davis, 1999, open-bigram models, Grainger & Whitney, 2005) predict an inhibitory effect of neighborhood frequency with transposed-letter neighbors. If higher frequency transposed-letter neighbors behave as higher-frequency substitution neighbors, we should find an inhibitory effect of neighborhood frequency in normal silent reading, particularly in “late” measures of word processing.

2. Experiment

2.1. Method

2.1.1. Participants

Eighteen students from the Universitat de València took part in the experiment. They received a small monetary compensation (3 €) for their contribution. All participants had normal vision and were native speakers of Spanish. They were all naive to the purpose of the experiment.

2.1.2. Materials

The stimuli comprised 36 pairs of sentences in Spanish (see Appendix A). The members of each sentence pair were identical except for the target word. In the experimental set, the sentence contained a target word which had a higher frequency transposed-letter neighbor (*guarida*-*guardia*; 16 pairs with a consonant–vowel transposition and 2 pairs with a consonant–consonant transposition), whereas in the other set the sentence contained a control word that had no transposed-letter neighbors. Words in the control condition were matched, on a pairwise basis, to the words of the transposed-letter neighbor condition in length ($M = 5.8$ letters in the two conditions, range 4–7) and word frequency ($M = 4$ per one million in the two conditions in the Spanish database [Davis & Perea, 2005]). The mean word-frequency of the higher frequency transposed-letter neighbor was 22.3 per million. Words in the higher-frequency transposed-letter condition and words in the control condition were also matched (all ps $> .50$) on the mean number of substitution neighbors (3.1 and 3.0, respectively), mean number of higher frequency substitution neighbors (1.0 and 1.0, respectively), number of higher frequency addition/deletion neighbors (0.3 and 0.15, respectively), and mean log bigram frequency (2.5 and 2.5, respectively). Words in the transposed-letter condition had no more than one higher frequency transposed-letter neighbor and, in all cases, this transposed-letter neighbor occurred in an adjacent internal position (position 2nd–3rd or 3rd–4th). We imposed this restriction because transposed-letter (nonword) neighbors that differ from a lexical item by an interior letter are likely to be more perceptually similar than those that differ by an external letter (e.g., see Johnson, Perea, & Rayner, 2007; Perea & Lupker, 2003; Rayner et al., 2006). Two sentences were made for each target word to minimize a potential effect of context, and also to make it possible to test the same words across two different sentences – that is, each word appeared for each participant but it was rotated across the two lists. Each sentence was no more than 62 characters in length, occupying one line on the display screen. Target words were always around the middle of the sentence.

2.1.3. Design

Two lists were created, each containing 36 sentences. Each list contained 18 target words (which had a higher frequency transposed-letter neighbor) and 18 control words. The sentences were counterbalanced across the two lists, so that the same sentence that included the target word in list 1, included the control word in list 2, and vice versa. This way, each participant read all words (experimental and control), thereby increasing statistical power. The order of presentation was randomized for each participant. To ensure that ease with which target words fitted into the sentential context was relatively balanced, we conducted a rating study in which 10 other participants saw the 36 pairs of sentences and were asked to rate the relative naturalness of the two sentences. They could respond that the sentence with the higher frequency neighbor was more natural, that the sentence with the control word was more natural or that both were equally natural, giving ratings of 1, -1 and 0, respectively (see Perea & Pollatsek, 1998, and Pollatsek et al., 1999, for the same procedure). The result of this test ($t = 0.32$, $SD = .50$) indicated that the items were balanced in terms of words fitting in the sentence.

2.1.4. Apparatus

The eye movements of the participants were recorded with an EyeLink II eye tracker manufactured by SR Research Ltd. (Canada). The sampling rate for the pupil size and location is of 500 Hz. The average gaze position error is less than 0.5°. Registration was binocular, although only data from the right eye was analyzed. The position of the participant respect to the screen was controlled by a head-tracking camera that served for compensating possible head motion.

2.1.5. Procedure

Participants completed this experiment in a well-lit soundproof room. Participants were sitting in a fixed chair that ensured a distance of 75 cm from the center of the screen. After the calibration and validation process, participants read four practice sentences for comprehension. Each trial started with the presentation of a fixation point that was left aligned (coinciding with the location of the first letter of each sentence). Participants had to gaze at that point, and the system automatically corrected any possible calibration drifts. When the fixation point disappeared from the screen, the target sentence was displayed. Participants were instructed to read for comprehension and to press one button in a gamepad as soon as they finished reading the sentence. To assure comprehension, they were asked to answer comprehension questions about the sentence they had just read after 20% of the sentences. Participants had little difficulty answering the questions correctly (94.5% of correct responses in each condition).

2.1.6. Data analysis

There are several ways to calculate the amount of time spent on the target word. Some dependent variables measure the "first pass" processing on the fixating word and include the first fixation duration and gaze duration. *First fixation duration* is the amount of time a reader spends on the initial fixation on the target word. *Gaze duration* represents the sum of fixation durations on a target word before the reader leaves that word. In addition, other dependent variables measure "late processes", once the reader leaves the target word on his or her first pass through the text (Perea & Pollatsek, 1998). Those measures include *spillover* (the duration of the first fixation – to the right – after leaving the target word), the probability of making a *regression* back to the target word and the *total time* spent on the target word (the sum of all fixation durations on the target word including regressive fixations).

3. Results

A few sentences were excluded from the analyses because of problems monitoring the eye movements (less than 1%). Fixations shorter than 80 ms or longer than 800 ms were deleted from the analyses. The reliability of the effects was assessed across both participants and items with transposed-letter neighborhood frequency (words with a higher frequency transposed–letter neighbor and words with no transposed-letter neighbors) as a within-item variable in the item analyses. List was also included in the analyses as a dummy variable to extract the variance due to the lists (Pollatsek & Well, 1995). All significant effects had p values less than the .05 level. The data are presented in Table 1.

3.1. First pass measures

First fixation duration, gaze duration, and skipping rate measures did not reveal any significant effects (all Fs < 1).

Table 1
Eye movement measures for the target words as a function of neighborhood frequency (standard deviation are presented in parentheses)

	With HF TL neighbors	With no TL neighbors
Percentage of skipping word (%)	13.9 (12.8)	16.0 (12.9)
First fixation duration (ms)	249 (30)	255 (33)
Gaze duration (ms)	325 (87)	324 (78)
Percentages of regressions (%)	35.8 (16.3)	19.5 (17.9)
Spillover (ms)	360 (65)	351 (79)
Total time (ms)	511 (180)	425 (123)

3.2. Late measures

The first measure that reflects late processing is the duration of the first fixation after the reader leaves the target word (spillover effect). This is often a noisy measure because the first fixation after the reader leaves the target word can be either on the word following the target or on the word following that (Pollatsek et al., 1999). We obtained a numerical nonsignificant inhibitory effect of transposed-letter neighborhood frequency (9 ms, both $ps > .10$) –which was close to the 12-ms effect reported by Perea and Pollatsek (1998). More important, the number of regressions back to the target word was significantly greater for words having a higher frequency transposed-letter neighbors than for control words (36 vs. 20% of regressions), $F1(1,16) = 22.63$, $MSE = 104.97$; $F2(1,34) = 14.14$, $MSE = 350.98$. Finally, the total time spent on the target word was 86 ms longer for words with a higher frequency transposed-letter neighbor than for words with no transposed-letter neighbors, $F1(1,16) = 27.92$, $MSE = 2416.05$; $F2(1,38) = 9.96$, $MSE = 16821.33$.

Finally, even though the materials were well matched across the relevant factors, it may be of interest to examine whether these variables accounted for significant variance, and more importantly, whether significant variance was still accounted for by the variable of interest. To do that, we conducted a multiple regression analysis on the two dependent variables that produced an effect of transposed-letter neighborhood frequency (i.e., regressions back to the target word and total time) with word-frequency, number of higher-frequency substitution neighbors, number of higher-frequency addition/deletion neighbors, log of bigram frequency, and transposed-letter neighborhood frequency (with vs. without transposed-letter neighbors) as predictors. Transposed-letter neighborhood frequency was a significant predictor of percentage of regressions back to the target word ($t(30) = 3.24$, $p < .004$) and of total time ($t(30) = 2.13$, $p < .05$). The other predictors did not show any significant effects (all $ps > .10$).

4. Discussion

The results of the present experiment are straightforward: there is an inhibitory effect of having a higher frequency transposed-letter neighbor in silent normal reading, thus extending the findings of Perea and Pollatsek (1998) with substitution neighbors. As expected, this effect was negligible in early pass measures (e.g., first fixation durations), whereas it was robust on late measures, particularly in the percentage of regressions and in the total time spent on the target word – as in the Perea and Pollatsek experiment.

Leaving aside that the present experiment is the first unambiguous demonstration of a transposed-letter effect with word neighbors – note that prior research on transposed-letter effects has focused on nonword stimuli (e.g., jugde) or on nonword-word pairs (e.g., *jugde-JUDGE*), the implications of the present results are clear: transposed-letter neighbors form part of a word's orthographic neighborhood. Furthermore, transposed-letter neighbors play an inhibitory role in word identification. This finding extends the inhibitory effect of transposed-letter neighborhood frequency in the error data reported by Andrews (1996) to a silent normal reading situation. As Andrews noted, most of the errors to the words with a higher frequency transposed-letter neighbor were precisely the pronunciations of these higher frequency mates. In the present experiment, it seems reasonable to deduce that a number of the regressions back to the target word were due to the reader initially misperceiving the lower-frequency transposed-letter neighbor by its higher frequency mate. One might argue that the obtained effect is not due to the frequency of the transposed-letter neighbor, but of the presence of a transposed-letter neighbor. However, Duñabeitia et al. (submitted for publication) failed to show any signs of a transposed-letter effect for words with lower frequency neighbors in normal silent reading when the participant's eye movements were monitored.

The present findings supports the orthographic coding schemes of the SOLAR model (Davis, 1999) and open bigram models (Grainger & Whitney, 2005): these models can readily account for the effects of neighborhood frequency with transposed-letter neighbors in terms of lateral inhibition at the lexical level. Interestingly, in the context of models of eye movement control, the late effect of neighborhood frequency can be readily captured by the E-Z Reader model (Reichle et al., 1998): neighborhood frequency effects would reflect lexical selection processes (L2 stage) that are obtained in late processing measures, as was the case in the present experiment – and in prior research with other types of "orthographic neighbors".

The presence of late competition effects in orthographic neighborhood effects in normal reading raises an interesting question: Does the biasing context affect the magnitude of neighborhood frequency effects? Given that some of the effects observed may be due to the (initial) misperception of the target word as the (higher-frequency) transposed-letter neighbor, it seems reasonable that, at least in some cases, participants misread the target word by its higher frequency neighbor, in particular when the higher-frequency neighbor fit in the sentence.[1] To test this possibility, we performed a *post hoc* analysis on the percentage of regressions back to the target word as a function of the transposed-letter mate's coherence in the sentence: in the experiment, there were 16 frames in which the transposed-letter mate fit in the sentence and 20 sentences in which the transposed-letter mate did not fit. The neighborhood frequency effect was larger for words with a higher-frequency transposed-letter neighbor that fit in the sentence (42 vs. 12% for transposed-letter words and control words, respectively) than for words with a higher-frequency transposed-letter neighbor that did not fit the sentence (31 vs. 24% for transposed-letter words and control words), as deduced by the significant interaction between neighborhood frequency and context, $F2(1,34) = 6.77$. Thus, albeit this analysis is *post hoc* and must be taken with caution, it suggests that the magnitude of neighborhood effects decreases when the target word's competitor does not fit into the context. Future research should be aimed at examining in detail how neighborhood effects differ depending on the biasing contexts when reading for meaning.

[1] We thank an anonymous reviewer for suggesting this analysis.

In sum, the present findings, taken together with others in the literature (Bowers, Davis, & Hanley, 2005; Davis & Lupker, 2006; Perea & Pollatsek, 1998; Pollatsek et al., 1999), indicate that there are effects of lexical competition when reading text for meaning. Furthermore, lexical competition occurs not only for substitution, addition or deletion neighbors, but also for transposed-letter neighbors. Therefore, the empirical evidence favors a competitive network in the visual word recognition system in which lexical inhibition plays an important role.

Appendix A. Sentences used in the experiment

The words used in the experiment appear into brackets. The word with a higher frequency transposed-letter neighbor is listed first. The word in italics enclosed by brackets at the end of the sentences is the higher frequency neighbor of the first member of the pair

Pablo puso el (clavo, gorro) en su sitio. *(calvo)*
No toques el (clavo, gorro) que he cogido del suelo.
Manuel tuvo que (clamar, aullar) de dolor con el martillazo. *(calmar)*
El lobo suele (clamar, aullar) fuertemente en señal de aviso.
Ayer vi un (cerdito, burrito) que tenía una herida en el lomo. *(crédito)*
He visto un (cerdito, burrito) en la entrada de tu finca.
La parte del (credo, cáliz) es la más aburrida de la misa. *(cerdo)*
El ritual del (credo, cáliz) es menos importante que la fe.
Marcos lleva este (odio, arma) consigo desde siempre. *(oído)*
Javier mostró su (odio, arma) a Paula.
Es evidente su (prejuicio, sobriedad) en cuanto hablas con ella. *(perjuicio)*
Me molesta su (prejuicio, sobriedad), pero lo acepto tal como es.
La incipiente economía (persa, sueca) está en proceso de crecimiento. *(presa)*
Tengo una amiga (persa, sueca) que viene a mi casa en verano.
No me hables del (plumón, guisar) del pajarraco. *(pulmón)*
Las aves de (plumón, guisar) son apreciadas en gastronomía.
Pedro enseñó el (truco, trigo) porque se lo pedimos. *(turco)*
Jaime mostró el (truco, trigo) detrás de la casa.
Si tienes un (aries, cardo) cerca has de tener cuidado. *(aires)*
Juan es un (aries, cardo) y tiene carácter, pero me gusta.
La miel de (cedro, brezo) se puede comprar en el mercado. *(cerdo)*
La flor del (cedro, brezo) es preciada para infusión.
El de esta (hornada, cestita) es el pan más crujiente. *(honrada)*
Se vendió la (hornada, cestita) de bollos esta misma mañana.
En el aula (magna, cutre) del primer piso tuvo lugar una charla. *(manga)*
La nueva decoración (magna, cutre) de la sala dio que hablar.
Sólo un tejido (raído, ileso) puede beneficiarse del tratamiento. *(radio)*
Si lo consideras (raído, ileso) ya no le dediques ni un segundo.
Tú tienes una (alergia, congoja) que vas a tener que buscar ayuda. *(alegría)*
Debido a mi (alergia, congoja) estoy desganada y apenas salgo.
Cuando empieza a (alienar, agobiar) la tarea es mejor dejarla. *(alinear)*
No te dejes (alienar, agobiar) por el trabajo y busca salidas.
Hay una gran (guarida, acequia) cerca de ese caserón. *(guardia)*
Ayer encontramos una (guarida, acequia) en pleno bosque.
Nada suele ser (causal, crucial) en la vida, todo es puro azar. *(casual)*
No puede ser (causal, crucial) esta relación entre variables.

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