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Transposed-letter and laterality effects in lexical decision

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Abstract

Two divided visual field lexical decision experiments were conducted to examine the role of the cerebral hemispheres in transposed-letter similarity effects. In Experiment 1, we created two types of nonwords: nonadjacent transposed-letter nonwords (*TRADEGIA*; the base word was *TRAGEDIA*, the Spanish for *TRAGEDY*) and two-letter different nonwords (orthographic controls: *TRATEPIA*). In Experiment 2, the controls were one-letter different nonwords (*TRAGEPIA*) instead of two-letter different nonwords (*TRATEPIA*). The effect of transposed-letter similarity was substantially greater in the right visual field (left hemisphere) than in the left visual field. Furthermore, nonwords created by transposing two letters were more competitive than the nonwords created by substituting one or two letters of a target word. We examine the implications of these findings for the models of visual word recognition.

Keywords: Letter encoding; Coding scheme; Lexical decision; Word recognition; Visual field

1. Introduction

One key issue for any computational model of visual word recognition is the specification of how letter identity and letter position are encoded during lexical processing (Davis & Bowers, 2004; Grainger & van Heuven, 2003). Although most researchers would agree that transposed-letter words such as *CAUSAL* and *CASUAL* are highly confusable, most models assume that letters are tagged to their position within a letter string very early in processing and then processed within their specific "channel" (e.g., interactive activation model, Rumelhart & McClelland, 1982; multiple read-out model, Grainger & Jacobs, 1996; dual-route cascaded model, Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001).

In the past years, there has been a growing interest on how letter identity and letter position are attained in visual word recognition, especially using transposed-letter stimuli (e.g., transposed-letter nonwords like *jugde* or words with transposed-letter "neighbors" like *trial–trail*). Robust transposed-letter similarity effects have been found in a variety of tasks, including lexical decision, naming, semantic categorization, speeded identification, and silent reading (Andrews, 1996; Chambers, 1979; Davis & Bowers, 2004; Gómez, Perea, & Ratcliff, 2003; Johnson, Rayner, & Perea, submitted; O'Connor & Forster, 1981; Perea & Lupker, 2003a, 2003b, 2004; Perea, Rosa, & Gómez, 2005; Schoonbaert & Grainger, 2004; Taft & van Graan, 1998). Interestingly, transposed-letter effects are not restricted to the transposition of adjacent letters. Perea and Lupker (2004) found that nonadjacent transposed-letter nonword primes produce robust priming effects relative to an orthographic control condition (e.g., *caniso–CASINO* vs. *caviro–CASINO*). Furthermore, nonwords created by transposing two nonadjacent letters are highly wordlike, with error rates around 40% (Perea & Lupker, 2004).

Taken together, these findings argue against a "position-specific" coding scheme such as that implemented in the interactive-activation model. In the past years, several models have been proposed that can readily account for the presence of transposed-letter similarity effects in reading (SERIOL model, Whitney, 2001; SOLAR model,

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Davis, 1999; overlap model, Gómez et al., 2003; open-bigram model, Grainger & van Heuven, 2003; split-fovea model, Shillcock & Monaghan, 2004). Two of these models (split-fovea and SERIOL) make specific predictions concerning the letter encoding process across cerebral hemispheres.

To explore in greater detail the nature of the letter encoding process, one useful strategy is to examine the role of the cerebral hemispheres in transposed-letter effects by using a divided visual field lexical decision task. The basic idea in a divided visual field experiment is that information to the left of fixation (i.e., right visual hemifield) is initially projected to the visual cortex of the left cerebral hemisphere, and information to the right of fixation (i.e., left visual hemifield) is initially projected to the visual cortex of the right cerebral hemisphere. There is empirical evidence that shows that the right and left hemispheres have a different sensitivity to factors such as word length (Whitney & Lavidor, 2004) and neighborhood size (Lavidor & Ellis, 2002a, 2002b): Word length has a greater impact when stimuli are presented in the left visual field, and the effect of neighborhood size occurs when the words are presented in the left visual field, but not in the right visual field.

But do brain hemispheres differ also as to the coding of letters within a word? In the framework of the split-fovea model, Monaghan, Shillcock, and McDonald (2004) suggested that the left and right hemispheres develop different representations of letter order. The left hemisphere would develop a coding based on individual letters, whereas the right hemisphere would develop a coarser coding based on activation of bigrams. Thus, this model can readily capture the interaction between neighborhood size and visual field, because bigram representations are more sensitive to letter context than are single-letter representations (e.g., see Whitney, 2004). More important, the split-fovea model predicts that a transposed-letter nonword (e.g., *relovución*) would be more perceptually similar to its base word (*revolución*) when it is presented in the right visual field (i.e., initially projected to the left hemisphere) than when it is presented in the left visual field. The reason is that the coarse coding in the right hemisphere for the transposed-letter nonword *relovución* would activate a number of bigrams that do not match the bigrams corresponding to its base word (e.g., *EL*, *LO*, *OV*, *VU*), whereas in the more "letter-sized" scheme of the left hemisphere, the transposed-letter nonword *relovución* would activate the same set of letters as the base word. It is important to mention that the position-specific encoding in the left hemisphere *is* sensitive to transpositions: in the split-fovea model, items are presented in all positions across the input, which obviates the problems of position-specific encoding (see Shillcock & Monaghan, 2004).

In the framework of the SERIOL model, Whitney (2004), Whitney and Lavidor (2004) argued that the encoding of letter position is the same for both hemispheres, and that the only differences occurred in the lateral inhibition in the serial firing of letters across hemispheres. There would be stronger lateral inhibition among adjacent letters in the right hemisphere (i.e., presentation in the left visual field) than in the left hemisphere (Whitney & Lavidor, 2004). For long strings, the SERIOL model predicts that letter-position encoding should be less accurate in the right hemisphere than in the left hemisphere.[1] While the stronger left-to-right lateral inhibition makes the right hemisphere locational gradient steeper than the left hemisphere across the early string positions, this inhibition 'bottoms up' for later string positions, and the net result is a non-optimal right hemisphere gradient, and an overall degraded encoding of letter order. In the SERIOL model, the stronger right hemisphere lateral inhibition arises at the (parallel) feature level, in the formation of an activation gradient that then brings about serial firing at the letter level. Other models (e.g., SOLAR model, overlap model, open-bigram model) remain neutral as to the role played by the cerebral hemispheres when encoding the order of letters within words.

The first aim of the present study is to examine whether transposed-letter similarity effects vary across hemispheres in a divided visual lexical decision task. To that end, we created transposed-letter nonwords by transposing nonadjacent letter positions (*tevelisión*) and their corresponding orthographic controls (two-letter different nonwords in Experiment 1; *tecetisión*; one-letter different nonwords in Experiment 2; *telecisión*). We used a single-presentation paradigm (i.e., words/nonwords were briefly presented to the right or to the left of a fixation point). In this "interference" technique, one would expect a higher rate of "word" responses and longer latencies for the (wordlike) transposed-letter nonwords than for the controls (see Perea & Lupker, 2004). For word targets, we manipulated word-frequency (high vs. low-frequency); as noted by Coney (2005), the large majority of divided visual field experiments obtained additive effects of visual field and word-frequency.

The second goal of this study is to examine whether transposed-letter nonwords created by transposing two nonadjacent letters (*tevelisión*) are more "competitive" (i.e., longer latencies and more false positives) than replacement-letter nonwords created by replacing *just* one letter (Experiment 2; *telecisión*). The results of Perea and Lupker (2003a) (see also Perea & Carreiras, in press) suggest that transposed-letter nonwords like *tevelisión* are highly word like, producing long response times and high error rates (around 40%). In another recent study, Perea et al. (2005) found that error rates for one-letter different nonwords (*telecisión*) were relatively low (around 15%). Taken together, these results suggest that, in a single-presentation technique, nonwords created by transposing two nonadjacent letter positions (*tevelisión*) may be more perceptually similar to their base words than the nonwords created by replacing a single

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[1] We thank Carol Whitney for her detailed explanation of the intricacies of the SERIOL model.

letter (*telecisión*).[2] However, the above comparison is not only across items but also across experiments. It is desirable to have the comparison within the same experiment. This is the aim of Experiment 2. Further, this is a critical experiment for discriminating among the coding schemes in visual word recognition (SOLAR model, SERIOL model, overlap model). Although the precise similarity of a target word (e.g., *casino*) and its nonadjacent transposed-letter nonword (*caniso*) depends on a variety of factors, the current parameter sets in the SOLAR and SERIOL models predict that a nonadjacent transposed-letter nonword like *caniso* is more similar to *casino* than a two-letter different nonword like *caviro*. For the default parameters of the SOLAR and SERIOL models, respectively, the similarity match to *casino* would be reduced to .81 and .83 for a one-letter different nonword like *casiro*, to .75 or .71 for the nonadjacent transposed-letter nonword *caniso*, and to .67 and .49 for a two-letter different nonword like *caviro* (see Perea & Lupker, 2004).[3] In contrast, the overlap model and the split-fovea model predict that nonadjacent transposed-letter neighbors can be more similar to their base words than one-letter different neighbors (Gómez et al., 2003; Shillcock & Monaghan, 2004).

2. Experiment 1

2.1. Method

2.1.1. Participants

Twenty-four students from the University of Santiago de Compostela received course credit for participating in the experiment. All of them either had normal or corrected-to-normal vision and were native speakers of Spanish. All subjects were right-handed, with scores of at least 80 in the Edinburgh Handedness Inventory (Oldfield, 1971).

2.1.2. Materials

For the word trials, we selected a set of eighty Spanish words of 7–10 letters. Forty of these words were high-frequency (mean word frequency per one million words in the Alameda & Cuetos, 1995; count: 63, range: 24–170; mean number of letters: 8.3). The other 40 words were low-frequency (mean word frequency: 9.5, range: 9–10; mean number of letters: 8.3). The base words for the nonword targets were 80 Spanish words of 7–10 letters (mean word frequency: 64, range: 26–210; mean number of letters: 8.3). To avoid any uncontrolled effects of initial syllable frequency (Perea & Carreiras, 1998), the nonwords maintained the initial syllable of their base words. For each base word we created: (i) a transposed-letter nonword in which two nonadjacent consonants were switched (*deyasuno*; the base word is *desayuno*, the Spanish for *breakfast*); (ii) a two-different letter nonword in which the two critical consonants were replaced by others with the same shape as in the transposed-letter nonword (e.g., *degavuno*). The position of the transpositions/replacements was around the word center, the mean was 4.65 (note that the mean number of letters in the experiment was 8.3, and that $[8.3 + 1]/2 = 4.66$). (For instance, in the eight-letter word *desayuno*, the transposed-letter nonword *deyasuno* would be around positions 3–5, and the word center would be between positions 4 and 5.) The syllabic structure of the transposed-letter nonwords and their controls was always the same as that of their corresponding base word. Bigram frequencies for transposed-letter nonwords and replacement-letter nonwords did not differ significantly ($p > .50$; Sebastián-Gallés, Martí, Carreiras, & Cuetos, 2000). Four lists of materials were constructed to counterbalance the items across visual field (left, right) and—for the nonword trials-type of nonword (letter-transposition, letter-substitution). Different groups of participants were used for each list. The stimuli were presented on 28 pt lowercase Tahoma. The letters appeared in black on a white background.

2.1.3. Procedure

Participants were tested individually in a quiet room. Presentation of the stimuli and recording of response times were controlled by SuperLab on a PC compatible computer. Participants sat at a viewing distance of 50 cm, with the head positioned in a chin rest. On each trial, a fixation point ("X") was presented at the center of the screen for 400 ms. Then, a target item was briefly presented (175 ms) to the left or to the right of the fixation point. The letter strings (words or nonwords) were presented at a displacement of 2.5° left or right the fixation point to the center of the letter string. Participants were instructed to press one of two buttons on the keyboard to indicate—as quickly and as accurately as possible—whether the letter string was a legitimate Spanish word or not ("—" for word and "Z" for nonword; for half of the participants the response keys were reversed—note that in a Spanish keyboard "—" is bottom right and "Z" is bottom left). Participants were instructed to keep their eyes on the central fixation point. Each participant received a different order of trials. Each participant received a total of 24 practice trials prior to the 160 experimental trials. The whole session lasted approximately 8 min.

2.2. Results and discussion

Incorrect responses (10.3% for word targets and 36.4% for nonword targets) and reaction times less than 250 ms or greater than 1500 ms (less than 1%) were excluded from the latency analysis. The mean latencies for correct responses and error rates are presented in Table 1. For word targets, participant (*F*1) and item (*F*2) ANOVAs based on

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[2] Nonetheless, in a series of masked priming experiments, Perea and Lupker (2004) found a 14-ms advantage of one-letter different primes (*casiro–CASINO*) over non-adjacent transposed-letter primes (*caniso–CASINO*), which suggests that a one-letter different nonword may be more perceptually similar to its base word than a non-adjacent transposed-letter nonword.

[3] We thank Colin Davis and Carol Whitney for providing us with the match scores.

Table 1
Mean lexical decision times (LDT, in ms) and percentage of errors (%E) for word and nonword targets in Experiment 1

	Words				Nonwords			
	High-frequency		Low-frequency		Transposed-letter		2_Letter-Diff	
	LDT	%*E*	LDT	%*E*	LDT	%*E*	LDT	%*E*
LVF	695 (92)	14.0 (9.2)	731 (93)	13.1 (10.0)	804 (112)	50.6 (17.5)	784 (103) 14.4 (13.8)	
RVF	631 (100)	5.8 (5.6)	675 (108)	8.5 (7.1)	824 (114)	65.4 (18.5)	776 (101) 15.2 (11.7)	
LVF–RVF	64	8.2	56	4.6	−20	−14.8	8	−0.8

Standard deviations are presented between brackets.
Note. LVF and RVF refer to left visual field and right visual field, respectively.

the participants' and items' response latencies and percentage error were conducted based on a 2 (Word frequency: high, low) × 2 (Visual field: left, right) × 2 (List: list 1, list 2) design. The factor List was included as a dummy variable to extract the variance due to the error associated with the lists. For nonword targets, participant and item ANOVAs based on the participants' and items' response latencies and percentage error were conducted based on a 2 (Type of nonword: transposition, control) × 2 (Visual field: left, right) × 4 (List: list 1, list 2, list 3, list 4) design. All significant effects had p values less than the .05 level.

2.2.1. Word targets

In the latency analysis, high-frequency words were responded to 40 ms faster than low-frequency words, $F1(1,22) = 21.16$, $MSE = 1798$; $F2(1,76) = 14.77$, $MSE = 4323$, and words presented in the right visual field were responded to 60 ms faster than words presented in the left visual field, $F1(1,22) = 30.04$, $MSE = 2883$; $F2(1,76) = 50.92$, $MSE = 37746$. There were no signs of an interaction between the two factors (both $ps > .15$).

In the analysis of the error data, words presented in the left visual field yielded more errors than words presented in the right visual field (13.5 vs. 7.1%, respectively), $F1(1,22) = 8.75$, $MSE = 110.8$; $F2(1,76) = 16.27$, $MSE = 99.3$. Neither the effect of word frequency nor the interaction between the two factors approached significance (all $ps > .15$).

2.2.2. Nonword targets

In the latency analysis, two-letter different nonwords were responded to 34 ms faster than transposed-letter nonwords, $F1(1,20) = 8.00$, $MSE = 3426$; $F2(1,53) = 7.19$, $MSE = 13507$. Neither the effect of visual field nor the interaction between the two factors was significant (all $ps > .15$).

In the analysis of the error data, two-letter replacement nonwords yielded substantially fewer errors than transposed-letter nonwords (14.8 vs. 58.0%, respectively), $F1(1,20) = 223.38$, $MSE = 200.8$; $F2(1,76) = 244.58$, $MSE = 611.2$. Nonwords presented in the right visual field yielded more errors than the nonwords presented in the left visual field (40.3 vs. 32.5%, respectively), $F1(1,20) = 9.60$, $MSE = 152.7$; $F2(1,76) = 13.42$, $MSE = 364.0$. The interaction between the two factors was significant, $F1(1,20) = 15.35$, $MSE = 75.2$; $F2(1,76) = 9.06$, $MSE = 430.1$, and reflected that the effect of visual field occurred for transposed-letter nonwords (50.6 vs. 65.4% of errors in the left and the right visual fields, respectively, $F1(1,20) = 17.40$, $MSE = 150.9$; $F2(1,76) = 17.35$, $MSE = 504.5$), but not for two-letter different nonwords (14.4 vs. 15.2% of errors in the left and the right visual fields, respectively, both $Fs < 1$).

The present results replicate the advantage in response times and error rates for the words presented in the right visual field relative to the words presented in the left visual field (Mishkin & Forgays, 1952; see also Coney, 2005; Ellis, 2004; Lavidor & Ellis, 2002a, 2002b, for recent evidence), and this effect is additive to the word-frequency effect (see Coney, 2005).

With respect to the nonword trials, transposed-letter nonwords were highly wordlike, replicating previous research (Perea & Carreiras, 2004a, 2004b; Perea & Lupker, 2004). More important, transposed-letter nonwords were especially "wordlike" when they were presented in the right visual field (i.e., initially processed in the left hemisphere).[4] The effect of visual field for nonword trials was restricted to transposed-letter nonwords, and it did not occur for replacement-letter nonwords.

3. Experiment 2

Experiment 2 is a replication of Experiment 1, except that the replacement-letter nonwords were created by replacing just one consonant letter (not two) from the base word (i.e., the one-letter different nonword for the base word *revolución* would be *revotución* or *remolución*). The aims were: (i) to replicate the visual field effect for transposed-letter nonwords, and (ii) to examine whether transposed-letter nonwords can be more competitive than one-letter different nonwords in a single-presentation lexical decision task.

3.1. Method

3.1.1. Participants

Sixteen students from the University of Santiago de Compostela received course credit for participating in the

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[4] It is important to stress that the very high error rates for the transposed-letter nonwords do not reflect a lenient decision criterion for "yes" responses; instead, they reflect the high degree of perceptual similarity between the transposed-letter nonwords and their corresponding base words (see Perea & Lupker, 2004; Perea & Carreiras, in press, for a similar pattern). For any skilled reader of Spanish, it is rather difficult to process/pronounce correctly a TL nonword such as *PRIVAMERA* under time pressure (the base word would be *PRIMAVERA*, the Spanish for *spring*).

experiment. None of them had taken part in Experiment 1. All subjects were right-handed, as determined by the Edinburgh Handedness Inventory—with scores of at least 80.

3.1.2. Materials

They were the same as in Experiment 1, except that the two-letter different condition was replaced by a one-letter different condition. For instance, the two-letter different nonword *remotución* was replaced by a one-letter different nonword (*revotución* or *remolución)*. To keep the replacement letter close to the word center, for half of the cases the chosen nonword was *revotución* and for the other half it was *remolución.* Bigram frequencies for transposed-letter nonwords and one-letter different nonwords did not differ significantly.

3.1.3. Procedure

It was the same as in Experiment 1.

3.2. Results and discussion

Incorrect responses (10.9% for word targets and 30.9% for nonword targets) and reaction times less than 250 ms or greater than 1500 ms (less than 1%) were excluded from the latency analysis. The mean latencies for correct responses and error rates are presented in Table 2. The statistical analyses were parallel to those presented in Experiment 1, except that the "two-letter different nonword" condition was replaced by the "one-letter different nonword" condition.

3.2.1. Word targets

In the latency analysis, high-frequency words were responded to 50 ms faster than low-frequency words, $F1(1,14)=24.66$, $MSE=1633$; $F2(1,76)=13.53$, $MSE=8897$, and words presented in the right visual field were responded to 43 ms faster than words presented in the left visual field, $F1(1,14)=14.29$, $MSE=2087$; $F2(1,76)=12.45$, $MSE=7268$. There were no signs of an interaction between the two factors (both $ps > .15$).

In the analysis of the error data, words presented in the left visual field yielded more errors than words presented in the right visual field (14.8 vs. 7.0%, respectively), $F1(1,14)=6.05$, $MSE=161.4$; $F2(1,76)=20.53$, $MSE=118.9$. The effect of word frequency approached significance in the analysis by participants, $F1(1,12)=3.40$, $MSE=46.0$, $p=.08$; $F2(1,76)=1.61$, $MSE=118.9$, $p>.15$. The interaction between the two factors did not approach significance (both $ps > .15$).

3.2.2. Nonword targets

In the latency analysis, one-letter different nonwords were responded to 63 ms faster than transposed-letter nonwords, $F1(1,12)=18.06$, $MSE=3552$; $F2(1,66)=10.00$, $MSE=22505$. The effect of visual field was not significant, both $Fs<1$. The interaction between the two factors was significant in the analysis by participants, $F1(1,12)=5.32$, $MSE=1457$; $F2(1,66)=0.30$, $MSE=21065$, $p>.15$, which reflected that transposed-letter nonwords were responded to 29 ms faster in the left visual field than in the right visual field, whereas one-letter different nonwords were responded to 15 ms slower in the left visual field than in the right visual field.

In the analysis of the error data, transposed-letter nonwords yielded substantially more errors than one-letter different nonwords (40.9 vs. 20.9%, respectively), $F1(1,12)=48.76$, $MSE=131.3$; $F2(1,76)=55.77$, $MSE=573.8$. Nonwords presented in the right visual field yielded more errors than nonwords presented in the left visual field (33.9 vs. 27.9%, respectively), $F1(1,12)=8.01$, $MSE=70.3$; $F2(1,76)=6.27$, $MSE=450.0$. The interaction between the two factors approached significance, $F1(1,12)=3.99$, $MSE=66.1$, $p=.06$, $F2(1,76)=2.94$, $MSE=449.2$, $p=.09$, and reflected that the effect of visual field occurred for transposed-letter nonwords (35.9 vs. 45.9% of errors in the left and the right visual fields, respectively, $F1(1,12)=10.04$, $MSE=79.7$; $F2(1,76)=6.6$, $MSE=606.1$), but not for one-letter different nonwords (20.0 vs. 21.9% of errors in the left and the right visual fields, respectively, both $Fs<1$).

As in Experiment 1, for word trials we found an effect of visual field which was additive to the effect of word-frequency. With respect to the nonword trials, we again found a robust effect of visual field on transposed-letter nonwords, whereas there were no signs of an effect of visual field on one-letter different nonwords. Finally, transposed-letter nonwords had substantially longer response times and more false positives than one-letter different nonwords (884 vs. 821 ms, and 40.9 vs. 20.9%, respectively).

4. General discussion

The main findings of the present experiments can be summarized as follows: (1) transposed-letter similarity effects for nonwords are robust and occur to a larger degree

Table 2
Mean lexical decision times (LDT, in ms) and percentage of errors (%E) for word and nonword targets in Experiment 2

	Words				Nonwords			
	High-frequency		Low-frequency		Transposed-letter		1_Letter-Diff	
	LDT	%*E*	LDT	%*E*	LDT	%*E*	LDT	%*E*
LVF	723 (108)	12.2 (11.5)	766 (129)	17.5 (11.9)	870 (160)	35.9 (10.7)	829 (123)	20.0 (11.8)
RVF	673 (85)	6.6 (6.5)	730 (106)	7.5 (5.8)	899 (142)	45.9 (14.4)	814 (122)	21.9 (13.6)
LVF–RVF	50	5.6	36	10.0	−29	− 10.0	15	−1.9

Standard deviations are presented between brackets. *Note.* LVF and RVF refer to left visual field and right visual field, respectively.

in the right visual field (left hemisphere) than in the left visual field (right hemisphere); (2) under peripheral presentation, nonwords created by transposing two nonadjacent letter positions (e.g., *tevelisión*) can be more perceptually similar to their base words (*televisión*) than the nonwords created by substituting just one letter (*telecisión*); (3) for word trials, the effects of word-frequency and visual field are additive (see Coney, 2005).

4.1. Transposed-letter effects and position encoding

The presence of transposed-letter similarity effects with nonadjacent letter positions (*relovución–revolución*) poses a problem for the models that assume a "position-specific" coding scheme (see Perea & Lupker, 2004). More important for present purposes, transposed-letter similarity effects were *greater* when the items were presented in the right visual field (left hemisphere) than when the items were presented in the left visual field (right hemisphere). This finding strongly suggests that the pattern of "word" activation invoked by transposed-letter nonwords varies across cerebral hemispheres. The presence of a visual field effect with transposed-letter nonwords is a demonstration of the high degree of "wordlikeness" of these stimuli. Bear in mind that researchers have typically failed to find a visual field effect for nonwords (see Lavidor & Ellis, 2002) and, indeed, this has also been the case for the replacement-letter nonwords in the present experiments.

The present findings are consistent with the predictions of the split-fovea model (Monaghan et al., 2004). In this model, the right hemisphere has a coarse coding (on the basis of bigram activation), whereas the coding of letters in the left hemisphere is developed on the basis of individual letters. The letter-sized units that are initially activated by the presentation of a transposed-letter nonword (e.g., *relovución*) in the right visual field (i.e., left hemisphere) make the letter string highly confusable with its base word. Note that transposed-letter nonwords share *all* the letters with their corresponding base words and that, despite the model using a slot-coding system, the stimuli in the split-fovea model are presented in all positions across each item (Shillcock & Monaghan, 2004). In contrast, the bigram-sized units that are initially activated by the presentation of a transposed-letter nonword in the left visual field make the letter string less confusable with its base word (i.e., some of the bigrams activated in the transposed-letter nonword do not match the corresponding bigrams in the base word; e.g., *EL*, *LO*, *OV*, *VU*). Of course, simulations on an implemented version of the split-fovea model would be needed to demonstrate this transposed-letter effect across cerebral hemispheres, and how the effect of transposed-letter similarity and the effect of orthographic neighborhood occur in opposite hemispheres.

Finally, as indicated in the Introduction, the SERIOL model (Whitney, 2001; Whitney & Lavidor, 2004) predicts that, for long stimuli (such as those employed in the present experiments), letter-position encoding should be less accurate in the right hemisphere than in the left hemisphere. To explain in further detail the observed transposed-letter effects in the context of a speeded word/nonword discrimination task in the SERIOL model, we need to assume that higher accuracy at detecting a transposed-letter nonword indicates a higher likelihood of detection, and a better encoding.[5] But rather than considering the detection of a transposition as a binary process, it may be more accurate to consider a transposition as having a graded effect, which merely reduces the activation level of the representation of the target words. Reduced activation would then make a negative response more likely. Under this scenario, for real words, the target word is less activated in the right hemisphere (because of impaired, coarse encoding), giving lower right hemisphere acceptance accuracy—thus explaining the main effect of visual field for word targets (i.e., words presented in the left visual field yielded more errors than words presented in the right visual field). The target is also less activated for right hemisphere transpositions (impaired encoding plus the effect of the transposition) than for left hemisphere transpositions (effect of the transposition), giving a higher right hemisphere rejection accuracy (i.e., nonwords presented in the left visual field/right hemisphere were classified as "nonwords" better than the nonwords presented in the right visual field/left hemisphere). For replacement-letter nonwords, the target is not very highly activated for either visual field, producing similar accuracy rates. Although the pattern of results seems to be consistent within the framework of the SERIOL model, simulations on an implemented version of the model would be needed to demonstrate this transposed-letter effect across cerebral hemispheres.

4.2. Transposed-letter nonwords vs. replacement-letter nonwords

Another important finding was that transposed-letter nonwords created by switching two nonadjacent letters were perceptually closer to their base words than the one-letter different nonwords, as deduced by the longer latencies and the higher rate of false positives in Experiment 2. This finding poses constraints on the models that have been proposed to capture transposed-letter similarity effects.

As indicated in the Introduction, the current versions of the SERIOL and SOLAR models predict that the similarity match between one-letter different nonwords and their base words should be higher than the similarity match between nonadjacent transposed-letter nonwords and their base words. It is, in principle, possible that a change in the parameter values in the SERIOL and SOLAR models could account for this effect. What we should also note is that, as predicted by these models, one-letter different nonwords are *better* primes than non-adjacent transposed-letter nonwords in masked priming experiments with central

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[5] We thank Carol Whitney for providing this reasoning.

presentations (*casiro–CASINO* vs. *caniso–CASINO*; e.g., Perea & Lupker, 2004). Thus, the two models predict the right pattern for priming experiments with standard (central) presentations. The most likely explanation for the apparent discrepancy between the Perea and Lupker (2004) experiments and the present experiments (with lateralized presentations) is that position uncertainty in peripheral vision is much greater compared to central vision (e.g., see Chung, Levi, & Legge, 2001).[6] Indeed, in the SOLAR model, changes in the sigma parameter (a parameter that reflects the degree of position uncertainty) may lead to predict that nonadjacent transposition neighbors are more similar to the base word than one-letter replacement neighbors, as actually happened in Experiment 2. (Note that, if the previous reasoning is correct, a replication of Experiment 2 with central presentations would lead to a higher error rate to one-letter different nonwords than to nonadjacent transposed-letter nonwords.) To explain the full set of data in the present experiments (i.e., the different pattern of transposed-letter effects across hemispheres), the SOLAR model would need to assume that the sigma parameter is higher for the left hemisphere (i.e., for the stimuli presented in the right visual field) than for the right hemisphere (i.e., for the stimuli presented in the left visual field).[7]

Finally, the overlap model can readily capture the greater similarity between a nonadjacent transposed-letter nonword and its base word than between a one-letter different nonword and its base word (see Gómez et al., 2003; also Ratcliff, 1981). In the overlap model, the assumption is made that letter representations extend beyond their specific letter position into neighboring letter positions. The encoding activation of a given letter at a specific letter position is represented as a Gaussian distribution with the peak of the curve falling at the correct letter position—the distribution, however, extends into other letter positions. Given that this encoding of letter position is noisy, the letter *v* in the transposed-letter nonword *relovución* is encoded at the fifth letter position as well as at adjacent locations, although to a lesser degree. In contrast, in the replacement-nonword *remolución*, the third letter, *m*, does not assist in activating the base word at all. The overlap model can therefore predict that nonadjacent transposed-letter nonwords (*relovución*) are more similar to their base words than replacement-nonwords which differ by only a single letter (*remolución*). At present, however, the overlap model remains neutral with respect to the role of the cerebral hemispheres in the encoding process.

In sum, the present study provides a demonstration of how letter position encoding varies across cerebral hemispheres. Further, we have shown that nonadjacent transposed-letter nonwords can be perceptually closer to their base words than one-letter different nonwords. Taken together, these findings pose constraints for the coding schemes that are currently being developed in the field of visual word recognition.

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[6] We thank Colin Davis for suggesting this point.

[7] In addition, in the open-bigram model (Grainger & van Heuven, 2003)—which is closely related to the SERIOL model (see Grainger & Whitney, 2004)—each ordered pair of letters activates "open" bigrams (up to a limit of two intervening letters). Thus, the word *casino* would activate 12 open bigrams *CA*, *CS*, *CI*, *AS*, *AI*, *AN*, *SI*, *SN*, *SO*, *IN*, *IO*, *NO*. In this model, the nonadjacent transposed-letter nonword *caniso* shares more bigrams with the base word than the replacement-letter nonword *casiro* does (eight vs. seven), and hence *caniso* is perceptually closer to its base word (*casino*) than *casiro*. Finally, the split-fovea model (Shillcock & Monaghan, 2004) may also predict that transposed-letter nonwords created by switching two nonadjacent letters are perceptually closer to their base words than the one-letter different nonwords; in this model, this would depend on the size of the receptive fields in the two hemispheres.

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