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Transposed-Letter Confusability Effects in Masked Form Priming

MANUEL PEREA
STEPHEN J. LUPKER

Most computational models of visual word recognition incorporate letter-position coding schemes according to which transposed-letter (TL) nonwords (e.g., jugde) are only moderately similar to their base words (e.g., judge). Nonetheless, TL nonwords are often misperceived as their base words, especially when the transposition of the letters occurs in middle positions (Chambers, 1979; O'Connor & Forster, 1981). To examine these issues further, we conducted three masked form priming experiments using a lexical decision task. In Experiment 1, form-related primes could be TL-internal nonwords, TL-final nonwords or the corresponding orthographic controls (e.g., uhser vs. ufner, ushre vs. ushno; the target would be USHER). Masked TL-internal primes produced a significant form priming effect (30 ms) relative to their orthographic control condition, an effect that was greater than the priming effect for TL-final primes (13 ms). Experiments 2 and 3 replicated these findings with a different set of prime-target conditions and a different set of items, respectively. Taken together, the results show that form priming effects can be found for TL primes relative to the appropriate orthographic control condition and that these effects are larger when the letter transposition is internal to the word than when it involves the final two letters. We discuss the implications of these results for the choice of a letter-position coding scheme in visual word recognition models.

When reading the sentence "Because of the impressive diligence of Judge Smith, the trail is now concluded," we might not notice any thing unusual. If so, it would be due to the fact that we had read the word trail as trial and that we had read the nonword jugde as judge. In both cases, we would have misperceived the order of the two letters that were physically transposed in the visual stimulus. The existence of transposed-letter (TL) confusability effects, such as these, has clear implications for theories of visual word recognition. Specifically, they imply that both letter identities and the positions of those letters within a letter string must be computed during the coding process.

In current computational models of visual word recognition, the assumptions about how letter positions are coded often are made somewhat arbitrarily and without much empirical grounding. Nonetheless, these seemingly theoretically irrelevant assumptions really are critical to the success or failure of the models because they determine which words are considered similar and, therefore, which word representations are most likely to be activated by a particular string of letters. As Andrews (1996) pointed out, limitations of the coding scheme can be a major contributor to a model's failure to successfully simulate human readers' data.

Undoubtedly, at some processing stage, letters must be encoded with respect to their position within a string because otherwise it would be impossible to determine the relative ordering of letters and, hence, to distinguish between words like trial and trail. Thus, all models must have some way of doing this. Computational models of visual word recognition such as the interactive-activation model (IAM; McClelland & Rumelhart, 1981), the activation-verification model (AVM; Paap, Newsome, McDonald, & Schvaneveldt, 1982), and the multiple read-out model (MROM; Grainger & Jacobs, 1996) use a channel-specific scheme: Each letter is immediately assigned a position-specific channel and then is processed completely independently within its own specific channel. As a result, fist is no more similar to fits than it is to fire as all three words have identical letters in only two of the four letter positions. Thus, this coding scheme would have great difficulty explaining the presence of TL confusability effects. Furthermore, in this coding scheme, the lexical selection processes for, say, four- and five-letter words would be essentially independent. That is, the word hose would only activate the lexical representations for four-letter words; therefore, it would not activate the lexical representation for house. Such a prediction is clearly inconsistent with the available evidence (e.g., de Moor & Brysbaert, 2000; Humphreys, Evett, & Quinlan, 1990; Perea & Carreiras, 1998; Peressotti & Grainger, 1999).

Recently, two extensions of the IAM have been proposed that can explain data suggesting that words like hose do activate the lexical representations of words like house. Jacobs, Rey, Ziegler, and Grainger (1998) proposed a relative-position coding scheme for the MROM (the MROM-p) in which the external letters are used as anchor points. In the MROM-p, letters in a word are represented in terms of their relative position in the word (relative to the initial or final position). For instance, the word trial would be encoded as T in the initial position, R in the initial plus one, I in the initial plus two, A in the final minus one, and L in the final position. Another coding scheme that uses a single system for words of various lengths (up to eight letters) is the one contained in Coltheart, Rastle, Perry, Ziegler, and Langdon's (2001) dual-route cascaded (DRC) model. According to this coding scheme, the word trial would be encoded as T in the initial position, R in the second position, I in the third position, A in the fourth position, L in the fifth position, whereas in positions six to eight there would be a blank-letter character. Although both of these models can explain why hose would activate the lexical representation for house, neither of these coding schemes can capture TL confusability effects.

An alternative to the use of a channel-specific coding scheme is to use context-sensitive encoding, such as with the "wickelfeature" scheme of the connectionist model of Seidenberg and McClelland (1989; see also Mozer, 1987, for a similar coding scheme using letter clusters). In this model, the basic unit is not the single letter but a group of ordered letters. For instance, the codes for trial would be _tr, tri, ria, ial, al_, where the sign _ refers to the end of the letter string. This type of coding scheme can predict the presence of partial-word priming. (The recognition of *WHITE* can be easier when the prime shares letters with the target, for example, o*it*k, than when the prime does not share any letters with the target, for example, foku (see Humphreys, Evett, & Quinlan, 1990; Peressotti & Grainger, 1999). However, it also cannot explain TL confusability effects.

Recently, other authors have suggested other coding schemes that appear to be more promising (SERIOL model, Whitney, 2001; SOLAR model, Davis, 1999). The SERIOL model uses a letter-tagging coding scheme, in which each letter is marked for the ordinal position in which it occurs within a letter string. For instance, the word slat would be represented by S-1, L-2, A-3, T-4. This letter-tagging scheme also is accompanied by the activation of bigram nodes — ordered pairs of letters—so that the word slat would be represented by the following bigrams: SL, LA, AT, SA, ST, and LT. This coding scheme can not only predict the presence of partial-word priming effects (i.e., *vitr-WHITE* versus *vefr-WHITE*; Humphreys et al., 1990) and it also can accommodate—to some degree—the presence of TL confusability effects. For instance, slat shares five bigram nodes with the TL neighbor salt (SA, SL, ST, AT, LT), which is more than the number it shares with the one-letter different neighbor scat (SA, AT, ST). Thus, slat would be more easily confused with salt than with scat.

Finally, the SOLAR model uses a spatial coding scheme in which letter codes are position-independent. As a result, the TL words salt and slat share the same set of letter codes. To account for the fact that any orthographic coding scheme must ultimately be order-sensitive, the order of letters in the SO-

LAR model is coded by the relative activity of the set of letter nodes. In this way, salt and slat share the same set of letter nodes, but they produce different activation patterns (e.g., in the word salt, the letter code corresponding to S is the one associated with the highest activation value, then the letter code corresponding to the letter A is associated with a slightly smaller activation value, and so on; see Fig. 4.1). Because serial position is coded by relative activities rather than via position-specific codes and because of the way the network computes bottom-up input, salt and slat are more similar and, hence, more confusable than slat and scat. Thus, the SOLAR model can readily explain TL confusability effects. Because of the special role of end letters in the model (see Davis, 1999), the SOLAR model also predicts that TL confusability effects should be greater when the transposition of letters occurs in middle positions than in external positions.[1]

A number of different strategies have been used in order to first establish the existence of and then to analyze TL confusability effects in visual word recognition. One strategy is to examine processing of TL words such as trial or trail (Andrews, 1996; Chambers, 1979; Taft & van Graan, 1998). Although the number of such pairs of words tends to be rather small, which makes it difficult to draw firm conclusions based on the results (see Forster, 2000), those results consistently show that the processing of TL words requires more time than the processing of control words. Another strategy is to examine processing of TL pseudowords (e.g., deciding whether JUGDE is a word or not in a lexical decision task). The results again suggest that at least TL-internal pseudowords (e.g., JUDGE) are more difficult to classify as being nonwords than one-letter different pseudowords (e.g., JUDPE) or control pseudowords (e.g., SLINT) (e.g., see Andrews, 1996; Chambers, 1979; Holmes & Ng, 1993; Perea, Rosa, & Gómez, 2002). However, the pattern of data for pseudowords does appear to

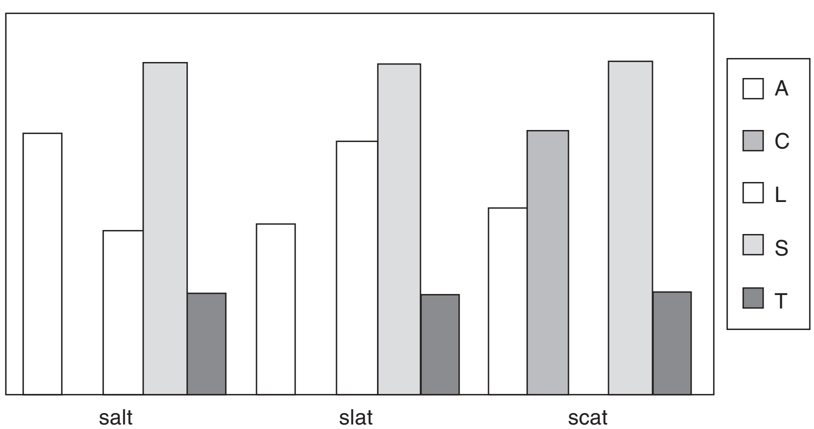

FIGURE 4.1. An example of spatial coding in the SOLAR model. The order in which letters occur is coded by the relative activity of nodes.

vary depending on the specific strategies that the participants are engaging in (e.g., Perea et al., 2002); hence, any observed effects may not generalize beyond the lexical decision task. Finally, a third strategy is to look for cross-position priming effects using a masked priming technique (e.g., Forster & Davis, 1984; Forster, Mohan, & Hector, this volume) with TL primes and word targets (e.g., *anwser-ANSWER*, Forster et al., 1987; see also Andrews, 1996; Castles, Davis, & Forster, this volume; Humphreys et al., 1990; Peressotti & Grainger, 1999). This option, which is the one used in the present experiments, has two advantages: (a) The (word) targets are kept constant across conditions, which avoids many potential confoundings in the materials (Forster, 2000); and (b) because the prime is briefly presented and masked, the nature of the observed priming effects gives a clear indication of whether early processing of the prime does activate the mental representations of TL words.

At this point, there is at least some evidence of cross-position priming effects from TL primes in visual word recognition (see Table 4.1). The first experiment that investigated the presence of these effects employed the four-field masking technique, in which lower case primes and upper case targets are presented very briefly, one after the other (for around 35 to 45 ms). Immediately before the prime and immediately after the target, pattern masks are displayed. Participants have to identify the target stimulus. Humphreys et al. (1990, Experiment 2b) found that the recognition of a target word (e.g., DOWN) was better when the prime was a TL-internal prime (e.g., dwon, 65.7%) than when the prime was unrelated (e.g., fsac, 53.2%). However, this effect was mostly due to the priming effect from the external letters, as deduced by the fact that performance in the orthographic control condition for the TL-internal primes (e.g., dsan; 62.6%) was only slightly worse than that for the TL-internal prime condition.

Forster et al. (1987, Experiment 1), using a masked priming procedure with a lexical decision task, provided slightly stronger evidence for the existence of TL priming effects. With a 60-ms prime-target SOA, Forster et al. found that, relative to an unrelated control condition, priming effects were similar for identity primes (e.g., *answer-ANSWER*, 64 ms) and for TL-primes (e.g., *anwser-ANSWER*, 63 ms), whereas priming effects were a bit smaller for one-letter different primes (e.g., *antwer-ANSWER*, 52 ms). This result suggests that TL primes can activate the representation of the target word to at least as large a degree as one-letter different primes can.

Using the same paradigm, Peressotti and Grainger (1999; Experiment 3b) found a significant, 19-ms masked priming effect when the prime consisted of the two external letters of the target word, and two internal transposed letters (always consonants; e.g., *bcln-BALCON*) relative to an unrelated control condition, at least with a 17-ms SOA. (The effect was less than 10 ms at the 33- and 50-ms SOAs.) Unfortunately, this effect is a bit difficult to interpret because Peressotti and Grainger did not include the appropriate orthographic control

TABLE 4.1. Previous Experiments that Have Examined the Presence of Cross-Position Priming Effects on Visual Word Recognition

Humphreys, Evett, and Quinlan (1990, Experiment 2B)	
Four-letter stimuli, perceptual identification task (four-field technique), dependent variable: % accuracy	
1234 identity priming condition (*sand-SAND*)	78.1
1324 TL priming condition (*snad-SAND*)	65.7
1dd4 orthog. control for TL condition (*smed-SAND*)	62.6
dddd unrelated condition (*rmet-SAND*)	52.3
(*Note.* Priming effects were similar for high- and low-frequency words.)	
Forster, Davis Schoknecht, and Carter (1987, Experiment 1)	
Six-letter stimuli, SOA = 60 ms, lexical decision task, dependent variables: RT and % errors (parentheses)	
Identity condition (*sailor-SAILOR*)	486 (3.8)
TL-condition (*salior-SAILOR*)	487 (5.1)
1-letter diff. condition (*sanlor-SAILOR*)	500 (8.5)
Unrelated word condition (*cheese-SAILOR*)	550 (12.5)
(*Note.* Priming effects were similar for high- and low-frequency words.)	
Peressotti and Grainger (1999; Experiment 3B)	
Six-letter targets, four-letter primes, lexical decision task, SOA = 17 ms, dependent variable: RT	
1346 priming condition (*blcn-BALCON*)	511
1436 priming condition (*bcln-BALCON*)	520
dddd (unrelated) priming condition (*tpvf-BALCON*)	539
Andrews (1996; Experiment 2)	
Four- to seven-letter stimuli, naming task, SOA = 56 ms, dependent variables: RT and % errors (parentheses)	
TL words (e.g., SALT*)*	
TL-priming condition (*slat-SALT*)	646 (11.8)
1-letter diff. condition (*saft-SALT*)	624 (6.4)
Unrelated word condition (*spin-SALT*)	632 (7.2)
Control words (e.g., SAND*)*	
TL-priming condition (*snad-SAND*)	622 (1.5)
1-letter diff. condition (*sant-SAND*)	609 (1.9)
Unrelated word condition (*soul-SAND*)	619 (2.0)

condition (brtn-BALCON). Thus, this effect could have resulted from priming from the two end letters.

In a naming task using the masked priming procedure, Andrews (1996; Experiment 2) found a robust inhibitory effect of TL word primes for TL target words (e.g., *slat-SALT*) relative to an unrelated word control (e.g., *spin-SALT*). Although this result was inhibitory rather than facilitative, it does clearly indicate an impact of TL primes on target processing. (The result itself was interpreted in terms of lexical inhibition across the TL words.) However, there were no signs of a TL priming effect from nonword primes (e.g., *snad-SAND*) relative to an unrelated word condition (e.g., *soul-SAND*), although the absence of an appropriate orthographic control condition (e.g., *smod-SAND*) makes this result difficult to interpret.

Finally, in an associative priming experiment using a lexical decision task with an 80-ms SOA (a prime duration of 40 ms followed immediately by a 40-ms pattern mask), Perea and Lupker (2001) found that masked TL-internal primes produce a significant associative priming effect (*ocaen-WAVES*, around 11 ms) relative to an unrelated condition. This effect was only a bit smaller than the associative priming for word primes (*ocean-WAVES*, 15 ms). In contrast, masked TL-final primes (ocena) did not yield a significant priming effect (Perea & Lupker, 2001, Experiment 2). Once again, however, these effects are difficult to interpret because the appropriate orthographic control conditions, that is, conditions that would allow an evaluation of the priming obtained from the letters shared by the primes and their base words (i.e., *ociun-WAVES* and *oceum-WAVES*) were not included.[2]

At this point, then, evidence for TL priming effects is somewhat mixed. Although there is evidence for such effects, much of it is derived from experiments that did not involve the appropriate orthographic control conditions. Thus, the observed effects could have resulted from priming, not from the TL-internal letters but from other shared letters, particularly, the first and last letters. It is worth noting that the quality of information about letter positions is better at the end of the word than for internal letters because of lateral interference (e.g., Estes, Allmeyer, & Reder, 1976; Jordan, 1990; Perea, 1998). Further, Humphreys et al. (1990; Jacobs et al., 1998) suggested that letters appear to be coded into some form of orthographic description in which their positions as internal or external letters are marked. If end letters are indeed this important, then the lack of an orthographic control condition that maintained the end letters makes it extremely difficult to attribute many of these priming effects to the TL manipulation. This line of argument suggests that it would also be useful to examine TL confusability effects when the transposition occurs in the end position (*judge-JUDGE*) as well as when it occurs at a middle position (e.g., *jugde-JUDGE*).

The main goal of the present research was to obtain additional evidence concerning these issues, that is, whether TL priming effects really do exist (compared to an appropriate control) and whether the position of the transposed letters (internal versus final) matters. To begin with, we wanted to provide a clear demonstration that TL nonwords do produce priming effects beyond those provided by the other letters in the prime. Second, following on Perea and Lupker's (2001) associative priming results, we wanted to analyze whether or not TL nonwords created by transposing adjacent internal letters (e.g., ocaen) produce more form priming than TL nonwords created by transposing the two final letters (e.g., ocena).

In Experiment 1 we compared the form priming effect for TL-internal and TL-final nonword primes using the appropriate orthographic control conditions. The words in this experiment were all five-letter words (e.g., usher). TL-internal primes were created by transposing either the second and third or third and fourth letters (i.e., either uhser or usehr). The appropriate orthographic control condition is one that maintains the other three letters in their original positions while substituting the two letters that were transposed (i.e., ufner or usatr). The TL-final primes were created by transposing the final two letters (i.e., ushre). The appropriate orthographic control condition is one that maintains the first three letters in their original positions while substituting the letters that were transposed (i.e., ushno). In this circumstance, whatever priming effects we get can be unambiguously interpreted as effects of our TL manipulation.

Experiment 2 was similar to Experiment 1, except that we also included unrelated control conditions (e.g., *bausn-USHER* and *bacse-USHER*) in order to evaluate the level of orthographic priming produced by the two types of orthographic control primes used in Experiment 1. Experiment 3 was a replication of Experiment 2 using six-letter stimuli, instead of five-letter stimuli.

EXPERIMENT 1

Method

Participants. A total of 36 University of Western Ontario students served as participants and received course credit for their participation. All of them either had normal or corrected-to-normal vision and were native speakers of English.

Materials. The targets were 120 words of five letters (mean word frequency per one million words in the Kučera & Francis, 1967, count: 78, range: 1 to 698; mean Coltheart's N: 3.7, range: 0 to 12). (Coltheart's N is defined as the number of words differing by a single letter from the stimulus, preserving letter positions; e.g., worse, and house are orthographic "neighbors" of horse; Coltheart, Davelaar, Jonasson, & Besner, 1977.) The targets were presented in upper case and were preceded by primes in lower case that were: (a) the same as the target (identity condition), e.g., *usher-USHER*; (b) the same except for a transposition of two internal letters (TL-internal condition), e.g., *uhser-USHER*; (c) the same except for a transposition of the two final letters (TL-final condition), e.g., *ushre-USHER*; (d) the same except for the substitution of two internal letters (the substitutions involved the same letter positions that were involved in creating the TL-internal prime condition; this condition serves as an orthographic control for the TL-internal condition), e.g., *ufner-USHER*;[3] (e) the same except for the substitution of two final letters (the substitutions involved the same letter positions that were involved in creating the TL-final prime condition; this serves as an orthographic control for the TL-final condition), e.g., *ushno-USHER*; or (f) an unrelated word (unrelated word condition).

An additional set of 120 nonwords of five letters was included for the purposes of the lexical decision task (mean Coltheart's N: 2.8, range: 0 to 10). The manipulation for the nonword targets was the same as that for the word targets (e.g., *merse-MERSE, mesre-MERSE, meres-MERSE, mexce-MERSE, meras-MERSE*), except that the unrelated control condition involved a nonword prime (e.g., *cleed-MERSE*). Six sets of materials were constructed so that each target appeared once in each, but each time in a different priming condition. Different groups of participants were used for each set of materials.

Procedure. Participants were run individually in a sound-attenuated room. Each trial consisted of a sequence of four visual events. The first was a forward mask consisting of a row of six hash marks (######). This mask was presented for 500 ms. The mask was immediately followed by the prime in lower case letters exposed for a duration of 40 ms, which was in turn immediately followed by a row of six hash marks (######) for a duration of 40 ms. Finally, the target in upper case letters replaced the mask, and remained on the screen until the response. (This procedure was the same as that used by Perea & Lupker, 2001.)[4] Each stimulus was centered in the viewing screen and was superimposed on the preceding stimulus.

Items were presented on a TTX Multiscan Monitor (Model No. 3435P). Presentation was controlled by an IBM-clone Trillium Computer Resources PC. The computer presented words as white letter strings on a black background. Reaction times were measured from target onset until the participant's response. Participants were asked to classify each letter string presented in upper case letters as a word or a nonword. No mention was made of the number of stimuli that would be presented on each trial. Participants indicated their decisions by pressing one of two response buttons. When the participant responded, the target disappeared from the screen. Each participant received a different random ordering of targets. Each participant received a total of 20 practice trials (with the same manipulation as in the experimental trials) prior to the 240 experimental trials. The whole session lasted approximately 16 minutes.

Results

Incorrect responses (4.4% of the data for word targets) and reaction times less than 250 ms or greater than 1,200 ms (less than 1% of the data for word targets) were excluded from the latency analysis. Mean latencies for correct responses and error rates were calculated across individuals. Subject ANOVAs based on the participants' response latencies and percentage error in each block were conducted based on a 2 (Orthographic relatedness: related, unrelated) × 3 (Type of relation: identity, TL-internal, TL-external) × 6 (List: list 1, list 2, list 3, list 4,

TABLE 4.2. Mean Lexical Decision Times (in ms) and Percentage of Errors (in Parentheses) on word and Nonword Targets in Experiment 1

	Type of prime		
	Related	Control	Priming
Word trials			
Word primes	523 (2.9)	570 (4.0)	47 (1.1)
TL-internal	556 (4.6)	586 (5.4)	30 (0.8)
TL-final	554 (5.0)	567 (4.3)	13 (–0.7)
Nonword trials			
Nonword primes	650 (10.4)	676 (9.7)	26 (–0.7)
TL-internal	646 (8.2)	668 (6.5)	22 (–1.7)
TL-final	654 (6.5)	659 (7.1)	5 (0.6)

list 5, list 6) design. The factor List was included as a dummy variable to extract the variance due to the error associated with the lists (see Pollatsek & Well, 1995). The mean response times and error percentages from Experiment 1 are presented in Table 4.2.

Word Data

RT Analyses. Not surprisingly, the main effect of relatedness was significant, $F(1,30) = 105.76$, $MSE = 464.4$, $p < .001$. The main effect of type of relation was also significant, $F(2,60) = 16.183$, $MSE = 660.9$, $p < .001$. More important, the magnitude of the priming effect differed as a function of type of relation, $F(2,60) = 5.92$, $MSE=862.9$, $p < .005$: There was a substantial identity priming effect (45 ms), $F(1,30) = 93.40$, $MSE = 424.2$, $p < .001$; the priming effect for TL-internal items was also significant (30 ms) $F(1,30) = 18.92$, $MSE = 875.4$, $p < .001$, whereas the 13-ms priming effect for TL-final items only approached statistical significance, $F(1,30) = 3.53$, $MSE = 875.4$, $p < .07$.

Error Analyses. The ANOVA on the error data did not yield any significant effects (all *ps* > .10).

Nonword Data

RT analyses. The main effect of relatedness was significant, $F(1,30) = 16.25$, $MSE = 835.1$, $p < .001$. The main effect of type of relation was not significant, $F(2,60) = 1.02$, $MSE = 913.4$, $p > .10$. More important, the interaction between the two factors approached significance, $F(2,60) = 2.60$, $MSE = 864.9$, $p < .084$: As with the RT data for word targets, there was a significant priming effect for nonword targets preceded by an identical prime (26 ms), $F(1,30) = 16.25$, *MSE*

= 742.4, $p < .001$, and for nonword targets preceded by a TL-internal prime (22 ms), $F(1,30) = 10.44$, $MSE = 832.3$, $p < .004$, whereas the 5-ms priming effect for TL-final items did not approach significance, $F(1,30) < 1$, $MSE = 990.3$.

Error Analyses. The ANOVA on the error data did not yield any significant effects.

Discussion

The results are reasonably clear-cut. If we use the respective control conditions as the baseline, we found a strong identity priming effect for word targets (47 ms) and, more importantly, we found a robust form priming effect for TL-internal primes (30 ms), clearly demonstrating the existence of cross-position priming from internal letters. In contrast, the form priming effect for the TL-final primes was rather weak (13 ms). The results for the nonword targets mimicked those of the word targets. In addition, it is worth noting that, unlike in the Forster et al. (1987) study, the latencies to word targets preceded by an identity prime were substantially faster than the latencies to word targets preceded by a related TL-internal prime (523 versus 556 ms, respectively), $F(1,30) = 36.51$, $MSE = 523.5$, $p < .001$.

Although our analysis of the results from Experiment 1 clearly shows that TL-internal primes produce more priming than TL-final primes, this conclusion must be made cautiously. The problem is that part of the reason for the larger priming effect for TL-internal primes (for word targets) was that the TL-internal orthographic control condition had a latency that was 19 ms longer than the latency for the TL-final orthographic control condition. The difference between the TL-internal and TL-final conditions was only 2 ms (556 versus 554 ms, respectively). Thus, if one were to only consider the performance in these two conditions, it would be hard to make a case that TL-internal and TL-final primes led to different size priming effects.

The question, therefore, is why was there a 19-ms latency advantage for the TL-final orthographic control condition over the TL-internal orthographic control condition? One possible answer is that the form priming available from the TL-final orthographic control primes (i.e., *ushno-USHER*) was stronger than the form priming available from the TL-internal orthographic control primes (e.g., *ufner-USHER*). That is, it is possible that the priming available from three identical initial letters (i.e., ush—) is greater than the priming available from three identical letters distributed as they were in the TL-internal orthographic control condition (e.g., u—er). The two TL-related conditions would, of course, also have differentially benefited from this part-word priming. Thus, it would be quite possible for the latency in the TL-final condition (i.e., ushre) to be equivalent to that in the TL-internal condition (i.e., uhser), even though the two TL priming effects were different sizes.

In order to obtain converging evidence on this point, in Experiment 2 we used two additional control conditions, that is, not only the orthographic controls, but also unrelated controls. These unrelated control conditions were designed to allow us to determine whether primes maintaining the first three letters (e.g., ushno) produce more form priming than primes maintaining the first, fourth and fifth (or first, second and fifth) letters (e.g., ufner). These conditions replaced the identity and unrelated word conditions from Experiment 1. The other four conditions remained constant so that we could determine whether the basic pattern from Experiment 1 would replicate.

EXPERIMENT 2

Method

Participants. A new group of 30 students received course credit for their participation. All of them either had normal or corrected-to-normal vision and were native speakers of English.

Materials and Procedure. Experiment 2 was identical to Experiment 1 except that the identity condition and the unrelated word condition were replaced by two new control conditions: (a) The prime was an unrelated nonword created by replacing two internal letters of a five-letter word (this condition serves as an unrelated control condition for the orthographic control condition for the TL-internal primes, e.g., *bausn-USHER*); or (b) the prime was an unrelated nonword created by replacing the fourth and fifth letters of a five-letter word (this condition serves as an unrelated control condition for the orthographic control condition for the TL-final primes, e.g., *bacse-USHER*). (An analogous modification was applied to create the nonword primes.) Note that these new conditions were created by re-pairing the primes and targets from the analogous orthographic control conditions (i.e., bausn and bacse are orthographic control primes for BACON). Because of the way the primes and targets were assigned to conditions, however, no prime was seen more than once by any participant.

Results

Incorrect responses (7.0% of the data for word targets) and reaction times less than 250 ms or greater than 1,200 ms (less than 1.2% of the data for word targets) were excluded from the latency analysis. Subject ANOVAs based on the response latencies and percentage error were conducted based on a 3 (orthographic relatedness: related, orthographic control, unrelated control) × 2 (type of TL manipulation: TL-internal, TL-external) × 6 (List: list 1, list 2, list 3, list 4, list 5, list 6) design. The mean response times and percentage error are presented in Table 4.3.

TABLE 4.3, Mean Lexical Decision times (in ms) and Percentage of Errors (in Parentheses) on Word and Nonword Targets in Experiment 2

	Type of prime				
	Related	Orthographic control	Unrelated	OC-priming	U-priming
Word trials					
TL-internal	562 (6.0)	584 (6.3)	584 (6.2)	22 (0.3)	22 (0.2)
TL-final	560 (8.0)	571 (9.5)	579 (6.2)	11 (1.5)	19 (–1.8)
Nonword trials					
TL-internal	653 (8.3)	656 (8.2)	658 (9.3)	–3 (–0.1)	5 (1.0)
TL-final	655 (10.5)	653 (10.3)	660 (9.2)	–2 (–1.3)	5 (–1.3)

Note: OC-priming refers to the difference between the orthographic control and the related condition and U-priming refers to the difference between the unrelated and the related condition.

Word Data

RT Analyses. The main effect of relatedness was significant, $F(2,48) = 10.47$, $MSE = 676.0$, $p < .001$. The main effect of type of TL manipulation was not significant, $F(1,24) = 2.06$, $MSE = 994.5$, $p > .10$. Although the interaction between the two factors was not significant, $F(2,48) < 1$, $MSE = 768.7$, the pattern was both similar to that of Experiment 1 and as predicted by our analysis. To begin with, there was an effect of relatedness relative to the orthographic control condition for the TL-internal primes (22 ms), $F(1,24) = 11.77$, $MSE = 676.0$, $p < .001$, but not for the TL-final primes (11 ms), $F(1,24) = 2.42$, $MSE = 768.1$, $p > .10$.[5] Once again, however, this was not due to the TL-internal condition being faster than the TL-final condition (562 versus 560 ms, respectively) but to the TL-internal orthographic control condition being slower than the TL-final orthographic control condition. Finally, note that, as expected, when one considers the unrelated control conditions, they had quite similar latencies. As a result, there was some hint of orthographic priming in the TL-final orthographic control condition (8 ms) but no such hint in the TL-internal orthographic control condition (0 ms), although the critical interaction was not significant ($F < 1$).

Error Analyses. The ANOVAs on the error data did not yield any significant effects (all ps > .10).

Nonword Data

None of the ANOVAs on the nonword data yielded any significant effects (all ps > .10).

Discussion

Note, first of all, that we once again observed the existence of form priming effects with TL primes. Further, as in Experiment 1, it appears that TL-internal primes produced more form priming than TL-final primes relative to the appropriate orthographic control conditions (22 versus 11 ms, respectively). Also as in Experiment 1, this result appears to be mainly due to the fact that the TL-final orthographic control condition had a shorter latency than the TL-internal orthographic control condition. Further, as hypothesized, the reason that the TL-final orthographic control condition had a shorter latency was that, based on the appropriate unrelated control conditions, there was more form priming in this condition than in the TL-internal orthographic control condition. However, one could, once again, argue that these claims are, to some degree, equivocal because none of these differences reached statistical significance.

In order to obtain additional evidence about this issue, it was felt that it was important to examine this phenomenon with a different set of items. Specifically, in Experiment 3, we examined TL priming effects using both the orthographic and unrelated control conditions with a set of six-letter words. (These conditions were the same as those in Experiment 2. In addition, as in Experiment 1, an identity priming condition and its appropriate control condition also were added.) In the framework of the SOLAR model, word similarity increases with stimulus length (i.e., bother and mother are more similar than both and moth). Empirically, Davis and Andrews (2001) found that TL confusability effects seem to be greater for longer rather than for shorter words. As a result, Experiment 3 should be a more powerful test of the interaction between TL relation (internal versus final) and form priming.

EXPERIMENT 3

Method

Participants. A new group of 32 University of Western Ontario students received course credit for their participation. All of them either had normal or corrected-to-normal vision and were native speakers of English.

Materials. The targets were 160 words of six letters (mean word frequency: 127, range: 43 to 492; mean Coltheart's N: 1.0, range: 0 to 6). The targets were presented in uppercase and were preceded by primes in lowercase that were: (a) the same as the target (identity condition, e.g., *budget-BUDGET*); (b) the same except for a transposition of the third and fourth letters (TL-internal condition, e.g., *bugdet-BUDGET*); (c) the same except for a transposition of the two final letters (TL-final condition, e.g., *budgte-BUDGET*); (d) the same except for the substitution of the two middle letters (the same letters that were replaced in the TL-internal condition; this condition serves as an orthographic control for the TL-internal condition, *bujfet-BUDGET*); (e) the same except for the substitution of the two final letters (the same letters that were replaced in the TL-final condition; this condition serves as an orthographic control for the TL-final condition, *budgfa-BUDGET*); (f) an unrelated word (unrelated word condition, e.g., *please-BUDGET*); (g) an unrelated nonword created by replacing the third and fourth letters of a six-letter word (unrelated control for TL-internal orthographic control condition, e.g., *ploise-BUDGET*); (h) an unrelated nonword created by replacing the fifth and sixth letters of a six-letter word (unrelated control for TL-final orthographic control condition, e.g., *pleaor-BUDGET*). (Once again, the primes in the unrelated control conditions were the same as those in the orthographic control conditions; however, these primes were paired with different targets.)

An additional set of 160 nonwords of six letters was included for the purposes of the lexical decision task (mean Coltheart's N: 1.7, range: 1 to 7). The manipulation of the nonword targets was the same as that for the word targets, except that the unrelated control condition involved a nonword prime. Eight sets of materials were constructed so that each target appeared once in each set, each time in a different priming condition. Different groups of participants were used for each set of materials.

Procedure. The procedure was the same as that used in Experiments 1 and 2.

Results

Incorrect responses (2.8% of the data for word targets) and reaction times less than 250 ms or greater than 1,200 ms (less than 1% of the data for word targets) were excluded from the latency analysis. Subject ANOVAs based on the participants' response latencies and percentage error were conducted based on a 3 (orthographic relatedness: related, orthographic control, unrelated control) × 2 (type of TL manipulation: TL-internal, TL-external) × 8 (list: list 1, list 2, list 3, list 4, list 5, list 6, list 7, list 8) design. We conducted a separate ANOVA to examine the repetition priming effects relative to an unrelated word condition for the word targets (or an unrelated nonword condition for the nonword targets). The mean response times and percentage error are presented in Table 4.4.

Word Data

RT Analyses. The main effect of relatedness was significant, $F(2,48) = 34.99$, $MSE = 827.5$, $p < .001$. The main effect of type of TL manipulation was not significant, $F(1,24) < 1$. More important, the interaction between the two factors was significant, $F(2,48) = 7.60$, $MSE = 626.7$, $p < .002$. Planned comparisons indicated that there was a significant priming effect (relative to the orthographic

TABLE 4.4. Mean Lexical Decision Times (in ms) and Percentage of Errors (in Parentheses) on Word and Nonword Targets in Experiment 3

	Type of prime				
	Related	Orthographic control	Unrelated	OC-priming	U-priming
Word trials					
Word primes	527 (2.5)		577 (2.8)		50 (0.3)
TL-internal	542 (2.0)	586 (2.8)	586 (3.1)	44 (0.8)	44 (1.1)
TL-final	552 (3.1)	564 (3.8)	591 (2.5)	12 (0.7)	39 (–1.3)
Nonword trials					
Nonword primes	645 (5.8)		661 (6.7)		16 (0.9)
TL-internal	649 (4.2)	659 (5.0)	655 (5.8)	10 (0.8)	6 (1.6)
TL-final	651 (5.2)	653 (6.1)	653 (6.3)	2 (0.9)	0 (0.2)

Note: OC-priming refers to the difference between the orthographic control and the related condition and U-priming refers to the difference between the unrelated and the related condition.

controls) for the TL-internal items (44 ms), $F(1,24) = 85.19$, $MSE = 349.6$, $p < .001$, whereas the priming effect for the TL-final items just reached the criterion for significance (12 ms), $F(1,24) = 4.27$, $MSE = 597.0$, $p=.05$, which is essentially the same pattern of results as in Experiments 1 and 2. Equally importantly, the difference between the orthographic control and the unrelated control conditions was significant for TL-final items (564 versus 591 ms, respectively), $F(1,24) = 31.65$, $MSE = 368.4$, $p < .001$, but not for TL-internal items (586 ms in both conditions), $F(1,24) < 1$. It is worth noting that, as in Experiment 2, if we use the unrelated control conditions as the baseline, TL-internal and TL-final primes showed similar size priming effects (44 versus 39 ms, respectively).

Finally, we found a robust identity priming effect (relative to the unrelated word condition), $F(1,24) = 37.91$, $MSE = 1065.8$, $p < .001$. Also as occurred in Experiment 1, latencies to word targets preceded by an identity prime were 15 ms faster than the latencies to word targets preceded by a related TL-internal prime (527 versus 542 ms, respectively), $F(1,24) = 4.74$, $MSE = 947.5$, $p < .04$.

Error Analyses. The ANOVA on the error data failed to reveal any significant effects (all $ps > .10$).

Nonword Data

The ANOVAs on the nonword data failed to reveal any significant effects, except for the presence of a 16-ms repetition priming effect (relative to the unrelated nonword condition) in the latency data, $F(1,24) = 5.98$, $MSE = 655.5$, $p < .025$.

Discussion

The pattern of priming effects for TL items was similar to that observed in Experiments 1 and 2 as well as being consistent with our previous analysis. Relative to the orthographic controls, there was a substantial priming effect for TL-internal primes (44 ms), whereas this effect was rather small for TL-final primes (12 ms). In contrast, relative to the unrelated control conditions, the priming effect was quite similar for TL-internal and TL-final primes (44 versus 39 ms, respectively). Equally importantly, there was a much larger form priming effect for the TL-final orthographic control primes (27 ms) than for the TL-internal orthographic control primes (0 ms) relative to the unrelated control conditions.

One question that could be raised concerning these effects would be whether they are dependent on the nature of the letters that were transposed. Specifically, Berent and Perfetti (1995) have proposed that it takes longer to identify vowels than consonants. If so, the priming effects we observe might depend on whether we have transposed two consonants (C-C), two vowels (V-V), or one of each (C-V). Further, because no attempt was made to match the TL-internal and TL-final conditions on this factor, the contrast between these two conditions may have been compromised. Fortunately, that does not appear to have been the case. In the TL-internal condition, the numbers of targets having C-C transpositions, C-V transpositions, and V-V transpositions were 35, 114, and 11, respectively; whereas in the TL-final condition, the numbers were 42, 117, and 1, respectively. Thus, it appears that the differences between the two conditions on this dimension were fairly small.

Interestingly, when one considers the targets in the TL-internal condition, there is some suggestion that the type of letter that was transposed did, indeed, matter. Comparing the related TL condition to the identity condition, we find that for the C-C transposition targets, there was no difference (i.e., latencies were 524 ms in the identity condition and 522 ms related TL-internal condition). For C-V transposition targets, the means were 523 ms and 541 ms, respectively, whereas for V-V transposition targets, the means were 504 ms and 557 ms, respectively. (The results for V-V transition targets must, of course, be regarded with caution because of the small number of targets involved.) Similarly, the priming effect for the related TL-internal condition (relative to the TL-internal control condition) was larger for C-C transition targets (62 ms) than for C-V transition targets (36 ms) and for V-V transition targets (51 ms).

Although this analysis is entirely post-hoc, it is suggestive of the idea that transposing consonants creates a more effective prime than any transposition involving vowels. What should be noted is that a similar analysis done on the TL-final targets showed no such pattern. The differences between the identity condition and the related TL-final condition were identical for the C-C and C-V targets (26 and 27 ms, respectively), whereas related TL-final C-V targets showed priming relative to the TL-final control condition (17 ms), although the

C-C targets did not (–2 ms). Whether it actually is the case that the type of letter being transposed matters and what the implications of such a finding would be for Berent and Perfetti's (1995) proposal must remain a matter for future research.

Finally, we should note that the difference between the identity condition and the related TL-internal condition with the six-letter words was substantially smaller than in Experiment 1 with five-letter words (15 versus 33 ms, respectively), which supports the idea that TL confusability effects tend to be stronger for longer words (see Davis & Andrews, 2001).

GENERAL DISCUSSION

The present experiments have demonstrated two basic findings that have implications for the issue of position coding in visual word recognition: (a) form priming effects can be found for TL primes relative to an appropriate orthographic control condition; and (b) these effects are larger when the letter transposition is internal to the word than when it involves the final two letters (*uhser-USHER* versus *ushre-USHER*).

The present results clearly support the idea that the coding of letter identity and the coding of letter position go on simultaneously (certainly for interior letters; see also Humphreys et al., 1990). Thus, the present data pose serious problems for models that use channel-specific coding schemes (e.g., the IAM, AVM, MROM, MROM-p, or the DRC model), that is, schemes in which the processing of letter identity occurs entirely within an already assigned channel. One way that these models could be amended would be to incorporate the idea that the coding of letter positions takes some period of time (at least for interior letters) and, often, position coding lags behind the coding of letter identities. Therefore, the argument would be that uhser primes USHER because until the letters are ultimately assigned to their proper channels, the system does not know that uhser is not usher and, hence, the mental representation for usher is initially activated. However, as indicated in the Introduction, new models have been proposed that use different coding schemes and, hence, potentially could explain TL confusability effects in a more straightforward way (e.g., SERIOL model, SOLAR model). We will discuss these models in a bit more detail in the next section.

TL-INTERNAL VERSUS TL-FINAL PRIMES

It appears that TL-final nonwords can only produce small form priming effects (around 11-13 ms) beyond the effects that are created by having identical letters in the initial word positions. They also appear to have little ability to produce associative priming effects (Perea & Lupker, 2001). In contrast, TL-internal primes can produce both associative priming effects (e.g., *ocaen-WAVES*; Perea & Lupker, 2001) and substantial form priming effects. This suggests than TL-internal primes allow greater access to the mental representation of their base words than TL-final primes (Fig. 4.2).

As noted, however, this conclusion that TL-internal primes produce more form priming than TL-final primes is based upon using a particular control condition. If we look only at the latencies for the TL prime conditions, they are actually rather similar for TL-internal and TL-final primes (the differences are –2, –2, and 10 ms in Experiments 1, 2, and 3, respectively). Thus, our argument that the TL priming effects are larger for the TL-internal primes has to be based on the claim that the TL-internal primes produce smaller form priming effects from the letters shared with the target than do the TL-final primes.

Direct support for this argument comes from the fact that the TL-final orthographic control primes (e.g., ushno) were better primes than the TL-internal orthographic control primes (e.g., ufner) when compared to the relevant unrelated conditions. The priming effects for these two control primes were 11 ms versus 0 ms in Experiment 2 and 27 ms versus 0 ms in Experiment 3. Indeed, there does not seem to be any real evidence that the TL-internal orthographic control primes produce any priming at all in spite of the fact that they share three or four letters with their targets.

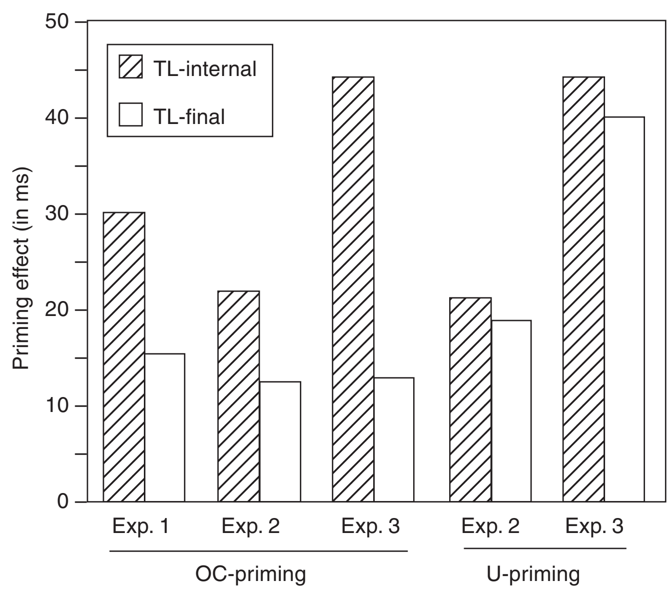

FIGURE 4.2. Form priming effects for word targets in Experiments 1, 2, and 3. OC-priming refers to the difference between the orthographic control and related conditions and U-priming refers to the difference between the unrelated and related conditions.

The presence of form priming effects for the TL-final orthographic control condition (*heavro-HEAVEN* versus *soewal-HEAVEN*), but not for the TL-internal orthographic control condition (*henoen-HEAVEN* versus *socite-HEAVEN*) is clearly at odds with claims about the importance of end letters (e.g., Humphreys et al., 1990; see Table 4.1). If end letters are important, primes that preserve them should be better primes. However, if there is a left-to-right component in the recognition process (e.g., see Davis, 1999; Whitney, 2001), these effects are not at all surprising. The TL-final orthographic control prime heavra and the target HEAVEN share the first four letters, whereas the TL-internal orthographic control prime henoen and HEAVEN share the two initial letters and the two final letters. In the SOLAR and the SERIOL models, the input to the letter level is serial (but rapid); thus, at time t_1 the letter H arrives, at t_2 the letter E, etc. This means that there is more opportunity for an activation pattern similar to that of the target to build up quickly from the heavra prime than from the henoen prime and, hence for heavra to be a better prime.

As noted in footnote 1, however, the SOLAR model also has a weighting parameter that allows the final letter in the prime to play a major role. Thus, as currently framed, this model has some difficulty explaining why heavra would be a better prime for HEAVEN than henoen would. This assumption, however, is not an essential component of the model and could be readily altered if the data ultimately compel it. What is also possible, however, is that there is another factor at play here as well, the internal structure of the target (see Forster & Taft, 1994). It is possible, for example, that a word target like HEAVEN is normally coded as two components, “HEAV” and “EN.” If so, then at least part of the reason heavra would be a better prime than henoen is because it preserves the entire first component of the target. In general, it would seem that a priming condition with three or four contiguous letters would be more likely to preserve potentially relevant orthographic units than a priming condition with three or four noncontiguous letters.

In sum, the absence of a latency difference between the two TL prime conditions does not appear to be due to the fact that the two TL priming manipulations per se (internal versus final) activate the target word to the same degree. The reason is that TL-internal primes do not produce any priming as a result of having three or four letters that are identical to those in the target. Thus, all the priming observed in these conditions was essentially owing to adding in the TL manipulation. Such was not the case for the TL-final primes. For those primes, most of the priming was due to the three or four overlapping letters, whereas the TL manipulation had only a minor impact.

One must be careful not to interpret this claim about the TL-internal primes too literally, however. The priming effects they produced were undoubtedly also due to the fact that the other three or four letters were the same as in the target. That is, the priming they produced was undoubtedly due to some type of interaction between the transposed letters and the remainder of the prime. If we had used primes containing only TL-internal letters but sharing no other letters with the target (e.g., *fovaom-HEAVEN*), it is unlikely that we would have observed much priming. Thus, the basic argument is simply that the pattern of activation across letter positions when there is a TL-internal prime (e.g., hevaen) is much more similar to the pattern of activation of the target (i.e., HEAVEN) than is the pattern of activation produced by a TL-internal orthographic control prime (e.g., henoen). In contrast, such is not the case when considering TL-final primes (e.g., heavne) and their orthographic control primes (e.g., heavra).

Finally, it is worth noting that we twice found significant repetition priming effects for nonword targets (26 ms in Experiment 1 and 15 ms in Experiment 3). Although the explanation of repetition priming effects for nonwords is a controversial issue (see Bodner & Masson, 1997 versus Forster, 1998), it now seems clear that these effects can be obtained using the standard masked priming procedure (i.e., lower case primes and upper case targets; e.g., Perea & Rosa, 2000; Sereno, 1991). However, as Forster (1998) noted, masked priming effects for nonword targets do tend to be small and unreliable. Such was the case here as well. That is, the repetition/form priming effects for nonwords tended to be much smaller in Experiments 1 and 3 than the parallel repetition/form priming effect for words. In any event, a discussion of the issues involved in masked repetition priming of nonwords is beyond the scope of the present chapter.

CONCLUSIONS

The present research demonstrated the existence of masked form priming effects produced by TL primes as well as demonstrating that those effects vary as a function of the TL letter positions: TL priming effects are stronger when the letter transposition occurs in the middle of the word than at the end of the word. These results are consistent with models that propose the existence of a spatial coding scheme (e.g., the SOLAR model), in which TL pairs are highly confusable, but not with models that assume some type of position-specific coding scheme.

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NOTES

1. The prediction of stronger TL confusability effects for the TL-internal item jugde than for the TL-final item jud*eg* in the SOLAR model results from the existence of a weighting parameter that favors a match in the external positions.
2. The fact that one-letter different primes (e.g., *ocern-WAVES*) did not produce a reliable associative priming effect in Perea and Lupker's (2001) experiments strongly suggests that the associative priming effect obtained with the TL primes was indeed a TL priming effect.
3. In all experiments, the replacement letters had similar shapes to the letters they replaced in the TL prime in terms of being ascending, descending or neutral letters.
4. The reason we used this procedure was that we wanted to keep the presentation parameters the same as those used in the Perea and Lupker (2001) experiments, given that both of these sets of experiments were concerned with internal versus final TL primes.
5. It is worth noting that if we combine the data from Experiments 1 and 2, the 12-ms form priming effect for the TL-final condition (relative to its corresponding orthographic control condition) is statistically significant, $F(1,54) = 5.81$, $MSE = 836.1$, $p < .02$.

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