An inhibitory influence of transposed-letter neighbors on eye movements during reading

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Abstract Previous research has shown that prior exposure to a word's substitution neighbor earlier in the same sentence can disrupt processing of that word, indicating that interword lexical priming occurs naturally during reading, due to the competition between lexical candidates during word identification. Through the present research, we extended these findings by investigating the effects of prior exposure to a word's transposed-letter neighbor (TLN) earlier in a sentence. TLNs are constituted from the same letters, but in different orders. The findings revealed an inhibitory TLN effect, with longer total reading times for target words, and increased regressions to prime and target words, when the target followed a TLN rather than a control word. These findings indicate that prior exposure to a TLN can disrupt word identification during reading. We suggest that this is caused by a failure of word identification, due to the initial misidentification of the target word (potentially as its TLN) triggering postlexical checking.

Keywords Eye movements · Reading · Psycholinguistics

Isolated-word recognition studies have shown that prior exposure to an orthographically similar word affects how rapidly a word is recognized (Andrews, 1997). Recent research has focused on the influence of substitution neighbors (words created from another word by the substitution of one letter,

preserving word length and letter order), showing that prior presentation of a substitution neighbor as a prime can inhibit subsequent target-word recognition, contingent on prime duration and the relative frequencies of the prime and target words (Coltheart, Davelaar, Jonasson, & Besner, 1977). For instance, when a masked prime is presented for a short duration (e.g., 60 ms), larger inhibitory effects are observed when the prime is of higher frequency (Davis & Lupker, 2006). Competitive network models of word recognition (Davis, 2010; McClelland & Rumelhart, 1981) attribute this effect to the higher-frequency neighbor prime giving a lexical competitor a “head start” in processing, thereby interfering with target-word recognition. By comparison, when an unmasked prime is presented for a longer duration (e.g., 250 ms), inhibitory effects are larger when the prime is of lower frequency (Segui & Grainger, 1990). In this case, conscious prime identification inhibits higher-frequency lexical competitors, impeding recognition of the higher-frequency target word.

Such findings are informative about the nature and time course of the orthographic influences on word recognition, and are fundamental to computational models of word recognition. But how these factors influence the lexical identification process during text reading has yet to be fully established. Several studies have shown that a word's lexical neighborhood can affect lexical identification during reading (Perea & Pollatsek, 1998; Slattery, 2009). For example, Perea and Pollatsek found that words with a higher-frequency substitution neighbor received longer total reading times than did control words, revealing that neighborhood effects occur naturally during reading. Moreover, other studies have shown that encountering a word's substitution neighbor a few words earlier in the sentence can influence fixation times on that word (Carreiras, Perdomo, & Meseguer, 2005; Frisson, Koole, Hughes, Olson, & Wheeldon, 2014; Paterson, Livversedge, & Davis, 2009). For instance, Paterson et al.

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found that prior exposure to a word's substitution neighbor (e.g., “blue”) rather than to a control word (e.g., “town”), in a sentence such as “In the photograph, the blue lights were a blur against the cold night sky,” produced longer fixations on the target word “blur.” This inhibitory effect emerged in the first fixation on the target word but was unaffected by the relative frequencies of the prime and target words, showing that interword priming effects occur naturally during reading. Frisson et al. subsequently showed that this effect is strongest when the neighbor word overlaps both orthographically and phonologically with the target. Wang, Tian, Han, Liversedge, and Paterson (2014) also demonstrated more recently an analogous effect in Chinese, in which prior exposure to a Chinese character that differs by one or two character strokes, and phonologically, from a target character can inhibit character processing.

These findings provide strong evidence for lexical competition during word identification during reading. However, the findings contrast with those from research using a word's substitution neighbor as a parafoveal preview in the boundary paradigm (Williams, Perea, Pollatsek, & Rayner, 2006). Here, when the neighbor appears in place of the target word before a saccade is made to fixate that word, facilitation rather than inhibition occurs. In this situation, the parafoveal preview activates the orthographic features of the word without strongly activating competing lexical entries, and target-word identification is facilitated. The indication, therefore, is that parafoveal preview of a word's neighbor does not initiate lexical competition, but that prior exposure to a word's neighbor earlier in the sentence can interfere with lexical/character identification.

It remains to be determined, however, whether other interword orthographic relationships affect word identification during normal reading and whether such effects are due to lexical competition. An important example concerns words formed by the transposition of two letters in one word to form another (e.g., “scared” and “sacred” are transposed letter neighbors [TLNs]). Such words reveal the role of a letter's position (as well as identity) during word processing, and in particular, whether letter position is encoded strictly or flexibly. Traditional word recognition models (McClelland & Rumelhart, 1981) assume that letter identity and position are encoded at the same time, resulting in a strict definition of orthographic similarity (*substitution neighbors*). However, evidence from experiments using TL nonwords has shown that TL nonwords produce greater activation of their base words than do letter substitution nonwords, resulting in a more flexible definition of orthographic similarity (Grainger, 2008). As a consequence, more recent models of letter position encoding assume that TLNs are more orthographically similar than substitution neighbors, predicting similar or even greater inhibitory effects than those for substitution neighbors (e.g., Davis & Bowers, 2006).

Evidence from isolated-word recognition studies using TLNs has been scarce and controversial. In some studies, TLNs have caused inhibitory effects that occurred at later stages of lexical processing (Andrews, 1996; Chambers, 1979), but in other studies these stimuli have produced null (Castles, Davis, & Forster, 2003; Duñabeitia, Molinaro, Laka, Estévez, & Carreiras, 2009; Duñabeitia, Perea, & Carreiras, 2009; Perea, Acha, & Fraga, 2008) or facilitatory (see Andrews, 1996; Castles, Davis, Cavalot, & Forster, 2007) effects. The inhibitory TLN effects are sometimes interpreted not as lexical competition, but as a failure of lexical access due to a target word's misidentification (e.g., Johnson, Staub, & Fleri, 2012). Inhibitory TLN effects in later eye movement measures are also observed when words with TLNs are embedded in sentences (Acha & Perea, 2008; Johnson, 2009), and studies using the boundary paradigm (Johnson & Dunne, 2012) have produced facilitatory effects similar to those reported by Williams et al. (2006) for substitution neighbors. It remains to be shown, however, whether the TLN effects that are observed between words that are encountered naturally during reading, without manipulations of parafoveal preview, are inhibitory or facilitatory.

Accordingly, in the present experiment we examined the influence of prior exposure to a TLN on the processing of words during reading. As in the study by Paterson et al. (2009), the TLN was encountered normally a few words earlier in the same sentence. If prior exposure to a TLN is facilitatory because prior identification of the TLN preactivates low-level orthographic information shared with the target word, target-word identification would be facilitated and shorter fixations would be made on that word. In contrast, if prior exposure to the TLN is inhibitory, this would slow target-word identification, producing longer fixation times on that word. A further issue concerns whether any such inhibitory effects emerge early or late during processing. If effects were observed early, this would suggest that prior exposure to a TLN produces lexical competition between the TLN and target words. However, if the effect occurred later during processing, this would suggest that the TLN caused the target word to be initially misidentified, resulting in postlexical checking.

Method

Participants

Twenty-eight undergraduate students ($M = 22$ years old) from the University of Southampton participated for course credits. All participants were native English speakers, had normal or corrected vision, and showed no evidence of reading difficulties, as assessed using the Wechsler Individual Achievement Test-II (Wechsler, 2005).

Materials and design

Twenty-nine sets of words between four and six letters long ($M =$ five letters) were selected. Each set comprised a target word (e.g., “sacred”), a TLN created by transposing two letters at interior locations (e.g., “scared”), and a control word created by substituting between one and three letters at interior locations (e.g., “snared”).¹ Each word of the triplet was the same length. The lexical frequencies from the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995) for the TLN ($M = 26.8$ counts/million) and control ($M = 21.7$ counts/million) words did not differ ($t < 1$).

Words from each set were inserted into an identical sentence frame so that either the TLN or the control word served as a prime and appeared a few words earlier in the same sentence as the target word (e.g., “The man found the *scared/snared* animal and wrapped his *sacred* football shirt around it”). A prescreen study using 72 participants (who did not participate in the eye movement experiment) confirmed that the target words were equally predictable, natural, understandable, and plausible in sentences containing either a TLN or a control prime word, and that the sentences did not differ in plausibility ($t_s < 1$) (see Table 1). The prime and target words were separated, on average, by 3.9 words (18.7 characters). The sentences were presented in counterbalanced lists so that for each participant, a sentence containing each target word was presented only once, and equal numbers of sentences containing either a TLN or a control-word prime were presented. In the experiment, we therefore manipulated prime type (TLN, control) as a within-participants variable. The key dependent variables were eye movement measures for the prime-word, target-word, and posttarget regions.

Apparatus and procedure

An EyeLink 1000 eyetracker recorded right eye movements. Forehead-and-chin rests were used to prevent head movements. The sentences were presented in 12-point, black Courier New font on the gray background of a 21-in. CRT monitor at a 60-cm viewing distance. Participants were instructed to read normally and for comprehension. Once a participant had finished reading a sentence, the participant pressed a response key, and 50 % of the sentences were replaced by a comprehension question, to which the participant responded. The experiment lasted about 20 min.

¹ Formal model comparisons between linear mixed-effects models that did and did not include a measure of orthographic overlap (the number of letters that varied between the target word and the prime) showed that this measure of orthographic overlap did not significantly improve the fit of the model to the data (chi-squared test, all $ps > .2$).

Results

Comprehension accuracy was high ($M = 83$ %). Following standard procedures, fixations under 80 ms and over 800 ms were deleted, as were fixations more than 2.5 standard deviations from each participant’s mean per condition (less than 4 %). In addition, short fixations (<80 ms), which were located within one character space of the next fixation, were merged into that nearby fixation. The data were log-transformed due to positive skew in the raw data. A range of eye movement measures were computed for the prime-word, target-word, and posttarget regions (comprising the next word after the target, or the next two words if the next word had fewer than four letters). For the prime and target words, we report first-fixation durations (i.e., durations of the first progressive fixation on words), single-fixation durations (i.e., durations of the fixation on a word fixated only once during first-pass reading), gaze durations (the sum of all first-pass fixations), total reading time (the sum of all fixations), regressions in (leftward saccades that land on the word), and second-pass reading time (the sum of fixations on a word following completion of first-pass reading of that word). In addition to these measures, for the target word only we report regressions out (backward eye movements from the word) and regression path reading times, which are the times from the initial fixation on a word until the eyes move onward in the sentence (Liversedge, Paterson, & Pickering, 1998). The duration of the fixation immediately prior to the first fixation on the target word was also examined, to ensure that any effects at the target word were not due to spillover effects from earlier text. Finally, for the posttarget region, we report the first-fixation duration, first-pass reading time (equivalent to the gaze duration for a region containing more than one word), and regressions out.

The data were analyzed with linear mixed-effects (lme) modeling using the lme4.0 package (Bates, Maechler, & Bolker, 2012) within R (R Development Core Team, 2013). For all analyses, Prime (TLN, control word) was specified as a fixed factor, and Participants and Sentences were specified as random factors in a full random structure (Barr, Levy, Scheepers, & Tily, 2013). All significance values, therefore, reflect both participant and sentence variability. Following convention, effects were considered significant when $t > 2$. Table 2 shows the means and standard errors for each measure.

Prime word

First-fixation durations were shorter for TLN primes than for control words ($b = .08$, $SE = .03$; $t = 3.06$). This effect was short-lived and was not observed in the later fixation time measures. It is consistent with facilitation of lexical access for TLNs compared to control words, due to the activation of orthographically similar words. This is also consistent with

Table 1 Means (*M*) and standard deviations (*SD*) of the linguistic properties for the two types of word primes—transposed-letter words (TL) and controls—and of the sentence ratings

	TL		Control	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Log lexical frequency (CELEX)	1.13	0.73	0.96	0.64
Neighborhood density (<i>N</i>) (<i>N_Watch</i>)*	4.30	3.61	6.37	3.99
Imageability (<i>N_Watch</i>)	491.5	117.26	549.69	72.71
Age of acquisition (Kuperman, Stadhagen, & Brysbaert, 2012)	6.91	1.59	6.42	1.84
Number of syllables (<i>N_Watch</i>)	1.37	0.56	1.27	0.45
SLFB (sum of log bigram frequencies; <i>N_Watch</i>)	11.38	2.32	11.87	1.84
MLFB (mean log bigram frequency; <i>N_Watch</i>)	2.8	0.34	2.94	0.28
Log bigram Frequency $\times$ Position (CELEX)	3.55	0.55	3.38	0.95
Predictability	0.09	0.29	0.07	0.26
Plausibility (1 <i>implausible</i> to 5 <i>plausible</i>)	3.26	1.29	3.39	1.26
Understandability (1 <i>easy</i> to 5 <i>difficult</i>)	2.00	0.53	1.95	0.51
Naturalness (1 <i>unnatural</i> to 5 <i>natural</i>)	3.40	0.52	3.46	0.50

Our *t*-test comparisons showed no significant differences between TL and control primes in any of the lexical characteristics reported ($p > .1$), except for the number of orthographic neighbors ($p < .001$). The *t*-test comparisons also showed no significant differences between the two types of primes in any of the sentence ratings ($p > .1$). In addition, targets were also equally predictable following both types of primes ($p > .4$). * Formal lme comparisons between a simple model and an lme model including the *N* showed that *N* did not play any role in the observed findings (chi-squared test, $p > .4$). This demonstrates that neither the linguistic properties of the types of primes nor the sentence ratings impacted on the findings observed in this study

facilitatory effects found with the TLNs of low-frequency words in both lexical-decision and naming tasks (Andrews, 1996, Exps. 1 and 2). In addition, second-pass reading times

were longer for TLNs than for control words ($b = -.14$, $SE = .07$; $t = -2.00$), indicating that readers spent more time reinspecting the TLN primes.

Table 2 Means (*M*) and standard errors (*SE*) for each condition—transposed-letter neighbors (TL) and control words (Control)—for each dependent variable in each region

		TL		Control		<i>t</i> > 2
		<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	
Prime word	First-fixation duration	228	4	251	6	*
	Gaze duration	272	6	286	7	
	Single-fixation duration	250	8	275	10	
	Total reading time	468	15	469	14	
	Regressions in	0.34	0.02	0.35	0.02	
Target word	Second-pass reading time	454	24	400	21	*
	Duration of fixation prior to first fixation on target word	210	4	215	4	
	First-fixation duration	235	4	230	4	*
	Gaze duration	266	6	261	6	
	Single-fixation duration	252	8	245	7	
	Total reading time	476	14	435	14	
	Regression path reading time	358	12	335	12	
	Regressions out	0.20	0.02	0.18	0.02	*
	Regressions in	0.43	0.02	0.38	0.02	
	Second-pass reading time	430	22	409	23	
Posttarget	First-fixation duration	228	5	235	6	*
	First-pass reading time	305	10	299	9	
	Regressions out	0.41	0.03	0.32	0.02	

* Significant ($t > 2$)

Target word

The durations of the fixation immediately prior to the first fixation on the target word showed no effects of the prime ($b = .02$, $SE = .02$; $t = 0.87$), indicating that the processing of earlier text did not spill over to the target word. No effects of the prime were observed in first-fixation durations, single-fixation durations, or gaze durations ($bs < .03$, $ts < 1.13$), either, indicating that the prime did not disrupt the initial processing of target words. However, clear prime effects were observed in total reading times ($b = -.10$, $SE = .04$; $t = -2.47$) and regression path reading times ($b = -.08$, $SE = .04$; $t = -2.14$), due to increased reading times for target words that followed a TLN rather than a control word. Crucially, the regression path effect indicated that the normal left-to-right progression of the eyes was impeded when the target followed a TLN prime. Moreover, the total-reading-time effect indicated longer reading times following revisits to the target word. No other effects were significant ($bs < .25$, $ts < 0.9$, $zs < 1.16$).²

Posttarget region

No effects of the prime were obtained in first-fixation durations or first-pass reading times ($bs < .01$, $ts < 0.34$), indicating that target-word effects did not spill over to the posttarget region. However, the prime type affected regressions from this region ($b = -.61$, $SE = .20$; $z = -3.08$, $p < .002$), with more regressions when the target word followed a TLN rather than a control word. This effect was consistent with misidentification of the target word following a TLN (Perea & Pollatsek, 1998). No other effects were significant ($bs < .08$, $ts < 1.71$).

Discussion

The present findings show very clearly that prior exposure to a word's TLN earlier in the same sentence can interfere with the processing of that word during reading. This extends the evidence of intrasentential, interword lexical-priming effects obtained previously for substitution neighbors (Carreiras et al., 2005; Frisson et al., 2014; Paterson et al., 2009). Here, we showed that this paradigm also produces effects between words that differ only in the order of two of their constituent letters.

An early facilitatory TLN effect was also found in first-fixation durations for the prime words. This effect is likely

to reflect the early coactivation of similar lexical representations (TLNs), which facilitated prime identification. Note that this effect occurred only at the prime word, was short-lived, and did not spill over so as to affect target-word processing. Furthermore, this effect was consistent with evidence from lexical and naming tasks, in which TLNs (of low frequency) are identified faster than their controls (Andrews, 1996, Exps. 1 and 2).

Studies of interword priming during reading that used substitution neighbors has shown early inhibitory effects on target-word processing (e.g., Paterson et al., 2009). In the present experiment, inhibitory TLN effects at the target word emerged only in regression path reading times, a measure of later processing. The regression path time includes fixations on the target word along with any fixations on previous words, until a fixation is made to the right of the target word. Thus, a significant proportion of the regression path time usually derives from fixations on the words preceding the target word (i.e., before the eye moves onward in the sentence). No effect was obtained in the gaze durations on target words, so the regression path effect must be driven by fixations that occurred after a regression from the target word to reread earlier parts of the sentence. Moreover, this increased rereading must have been triggered at the target word by prior exposure to its TLN. Two conclusions follow from this. First, in contrast to previous research with substitution neighbors, prior exposure to a TLN appears not to have triggered lexical competition during target-word identification, due to the lack of early effects on the target word. Second, the disruption to processing that we observed is consistent with readers initially misidentifying the target word, potentially misreading it as the previously encountered TLN (e.g., Johnson, 2009). Such misidentification may have led to failure to integrate the target word into the current sentence interpretation, resulting in processing disruption. In our example “The man found the *scared* animal and wrapped his *sacred* football shirt around it,” we are suggesting that readers would initially misidentify the word “sacred” as the word “scared.” However, this word does not fit the context, so readers detect this misidentification. Presumably, readers are aware that they have recently encountered an orthographically similar word, and so will often regress back to that word's location to verify whether the prime and target are the same or slightly different words. Consistent with this explanation, we obtained a reliable inhibitory second-pass effect on prime words. In addition, we obtained an inhibitory TLN prime effect at the target word in total reading times, indicating increased revisits to the target word after initially encountering it. Presumably this effect reflects checking processes to confirm the identity of the prime word relative to the target word.

It could be argued that these effects reflect lexical competition late during lexical processing. For example, Perea and Pollatsek (1998) found inhibitory substitution-neighbor

² We also conducted formal comparisons of lme models with and without the relative frequencies of the prime and target words, and found that including the relative frequencies did not significantly improve the fit of the model to the data (chi-squared test, all $ps > .1$).

effects in total and regression path reading times for target words, and also spillover effects and regressions back (to the target) for a posttarget region (see also Acha & Perea, 2008; Johnson, 2009). They argued that because the inhibitory effect was obtained in the first fixation on the posttarget region, this represented competition during later stages of lexical identification. In such a situation, lexical processing would be ongoing following the initiation of a progressive saccade. In our experiment, neither early inhibitory TLN effects at the target words nor spillover effects at the posttarget region were observed, so it is unlikely that this account applies to the present findings. Instead, the misidentification account that we propose seems more likely. This is also consistent with previous evidence that has shown the lack of a TLN effect using isolated-word paradigms (Castles et al., 2003; Duñabeitia et al., 2009a, b; Perea et al., 2008).

So why do TLNs, but not substitution neighbors, cause postlexical checking? First, TLNs share more orthographic information (an identical letter set) than do substitution neighbors (with one letter different), and so are perceptually more confusable. This may increase the likelihood of misidentifying a TLN, producing increased postlexical checking. Second, identification of the correct candidate may be inhibited at the target word due to this word already being partially activated when the prime was first encountered and identified. As we have already mentioned, an early facilitatory effect was found at the prime region, suggesting that having a TLN facilitates prime identification. Once the prime was fixated and identified, the other member of the TLN pair (the target word) would have been inhibited. Assuming that prime activation remained greater than that associated with the target as the eyes progressed through the sentence, upon encountering the target, the prime would be more strongly activated than the target. This, in turn, might trigger misidentification of the target as the prime. Indeed, this second possibility is consistent with an episodic-memory approach to word recognition (e.g., Tenpenny, 1995), which assumes that, when the same (or a similar) word is presented repeatedly, the word is identified faster because episodic-memory traces associated with its prior encounters are evoked. But, whatever the exact explanation, it is clear that prior exposure, and therefore identification, of a word's TLN caused disruption to the processing of that word due to its misidentification, triggering postlexical checking.

Computational models of isolated-word recognition cannot readily explain postlexical checking during reading, quite reasonably, because they were designed primarily to explain the lexical identification of isolated words. Some computational models of eye movements during reading distinguish between lexical and postlexical processing (e.g., the E-Z Reader model; see Reichle, 2011). However, the nature of lexical processing in such models remains underspecified—quite reasonably, given that the primary objective of these models is to account

for eye movement control and not for word recognition. In our view, this reflects the current position in understanding the processes underlying reading, and researchers (including ourselves) seeking a fuller understanding of these processes must develop accounts of lexical processing that can be realistically incorporated into models of eye movement control. Such accounts would aim to explain how lexical processing is distributed across successive fixations and would employ both partial (parafoveal), as well as fully available (foveal), visual information for word recognition (see Grainger, 2000; Rayner & Liversedge, 2011, for similar views).

In summary, the present study provides novel findings relating to TLN intrasentential, interlexical priming during reading. We showed evidence of TLN influences at a prime word early in the sentence, as well as effects consistent with lexical misidentification of a TLN target word downstream in the sentence. Overall, the present findings reveal more fully how the orthographic neighborhood impacts on lexical and postlexical processing during reading.

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