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BRIEF REPORT

Transposed-letter priming effects in reading aloud words and nonwords

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Abstract A masked nonword prime generated by transposing adjacent inner letters in a word (e.g., *jugde*) facilitates the recognition of the target word (JUDGE) more than a prime in which the relevant letters are replaced by different letters (e.g., *junpe*). This transposed-letter (TL) priming effect has been widely interpreted as evidence that the coding of letter position is *flexible*, rather than *precise*. Although the TL priming effect has been extensively investigated in the domain of visual word recognition using the lexical decision task, very few studies have investigated this empirical phenomenon in reading aloud. In the present study, we investigated TL priming effects in reading aloud words and nonwords and found that these effects are of equal magnitude for the two types of items. We take this result as support for the view that the TL priming effect arises from noisy perception of letter order within the prime prior to the mapping of orthography to phonology.

Keywords Transposed-letter (TL) priming effect · Reading aloud · Computational models of reading aloud

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How are we able to "raed wrods with jubmled lettres"? It is now well-established that readers are tolerant of distortion to the correct order of letters within a word (e.g., Perea & Lupker, 2003; Rayner, White, Johnson, & Liversedge, 2006). In the last decade, this issue has been primarily investigated using the masked priming paradigm: a briefly presented nonword prime created by transposing two adjacent inner letters in a word ("transposed-letter (TL) prime", e.g., *jugde*) facilitates the recognition of the original (target) word (e.g., JUDGE) compared to nonword primes in which the relevant letters are replaced by unrelated letters ("Replaced letter (RL) prime", e.g., *junpe*). This TL priming effect suggests that letter position is coded *flexibly*, rather than *precisely*, thus posing a challenge to computational models of reading that adopt a *slot-based* letter coding scheme (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Grainger & Jacobs, 1996; Perry, Ziegler, & Zorzi, 2007; Norris, 2006). According to the slot-coding scheme, letter identities are associated with a precise position within a word, and so the primes *jugde* and *junpe*, which both share the letters J, U, E with the target JUDGE in positions 1, 2, and 5, respectively, are assumed to be equally similar to this word. The TL priming effect is at odds with this assumption.

None of the available computational models of *reading aloud* (e.g., Coltheart et al., 2001; Perry et al., 2007; Plaut, McClelland, Seidenberg, & Patterson, 1996) has sought to account for the TL priming effect. Indeed, Perry et al. (2007) identified a list of benchmark effects that the next generation of computational models of reading aloud should be able to explain (see p. 301); the TL priming effect does not appear in this list. This is perhaps because the TL priming effect has been primarily observed in visual word recognition tasks, such as lexical decision, which do not a priori require the generation of phonology. Furthermore, the available empirical evidence for this effect in the reading aloud domain is scarce, and the few studies that investigated TL priming effects in reading aloud used only word targets (Andrews, 1996, Experiment 2; Christianson, Johnson, & Rayner, 2005; Johnson & Dunne, 2012). A key assumption in models of reading aloud within the dual-route framework (e.g., the DRC model, Coltheart et al., 2001; the CDP+ model, Perry, et al., 2007) is that there are at least two procedures involved in the translation of orthography to phonology; a lexical procedure which is restricted to words, and a sublexical procedure which uses subword information to translate unfamiliar words or nonwords into speech sounds. Thus, in order to develop further such models it is important to establish whether the sublexical procedure is sensitive to TL priming effects. That is, will we observe TL priming with nonword targets?

Extant accounts of TL priming effects make different predictions about the presence of these effects with nonword targets. According to the "open bigram" models (e.g., Grainger & van Heuven, 2003; Whitney, 2001), for example, nonword targets are not expected to yield TL priming effects. Open bigrams are ordered letter pairs that can be non-contiguous: For example, JUDGE consists of the open bigrams JU, JD, JG, UD, UG, UE, DG, DE, and GE (all current open bigram models assume that open bigrams can span up to two intervening letters). A TL prime shares more open bigrams with the target word than a RL prime: *jugde* contains seven out of eight open bigrams (all except DG) that code JUDGE, whereas *junpe* shares only two open bigrams with JUDGE. As such, the former is more likely to activate the target word compared to the latter, thus yielding TL priming. Proponents of open bigram theories acknowledge that open bigrams are unsuited to generating phonology sublexically: A sequence of serially ordered phonemes (e.g., /k/ - /ae/ - /t/) cannot be generated from an unordered set of bigrams {CT, AT, CA}. Accordingly, Whitney and Cornelissen (2008) argued that their open bigram representation is "taken to be specific to the lexical route" (p.160) and that "letter order is encoded more reliably on the sublexical route" (p.161). Other open bigram models (e.g., Grainger & van Heuven, 2003; Grainger & Ziegler, 2011) similarly assume that open bigrams serve as an intermediate level of orthographic representation between letters and words within the lexical procedure, and that open bigrams are not represented in the sublexical procedure ("precise letter order information is required along the fine-grained processing route that generates a sublexical phonological code," Grainger & Ziegler, 2011, p. 5). According to open bigram models then, TL priming effects are not expected when reading aloud nonword targets.

In contrast, according to the Overlap model (Gomez, Perea & Ratcliff, 2008) and the noisy channel model (Norris & Kinoshita, 2012), TL priming effects should not be limited to word targets. The key idea here is that TL priming effects arise because of perceptual noise early on in processing; during the brief time the TL prime *jugde* is available, letter position information (whether G is to the left or to the right of D) is ambiguous. Over time (i.e., with more opportunity for perceptual sampling from the input), the uncertainty in letter position is resolved, giving rise to an orthographic representation where letter order is precisely specified. This evolving prelexical orthographic representation serves as the input to the lexical and sublexical procedures, thus yielding TL priming effects for both words and nonwords. According to these models then, both word and nonword targets are expected to yield TL priming effects.

In sum, only a few studies have investigated TL priming effects in reading aloud, and none has tested whether such effects are obtained with nonword targets. In the present study, we sought to fill this gap in the literature with a view to providing empirical data that are critical for the further development of computational models of reading aloud. Existing accounts of TL priming effects make different predictions in relation to whether these effects will be observed with nonword targets. Open bigram models consider these effects to arise only within the lexical procedure, whereas the Overlap and the noisy channel models assume that the origin of these effects is prelexical. As such, the latter, but not the former, predict TL priming effects for nonword targets. In the present study, we sought to test these predictions by investigating TL priming effects in word and nonword reading aloud.

Experiment

Method

Participants Thirty-two undergraduate students from Macquarie University participated in the study for course credit. Participants were native speakers of Australian English and reported no visual, reading, or language difficulties.

Materials and design The targets consisted of 50 words and 50 nonwords that were monosyllabic, four letters long, and had a CVCC structure (e.g., BENT, BIMP). The target words were of low–to–moderate frequency (mean 13.22, range 25–84.08 per million) according to SUBTLEX (Brysbaet & New, 2009) with a mean orthographic neighbourhood (*N* as per Coltheart, Develaar, Jonasson, & Besner, 1977) of 10.64 (range 3–16). The target nonwords were generated by appending a consonant onset to a consistent body (e.g., -EST, -INK). Their mean *N* was 7.02 (range 1–20). For each target, two nonword primes were generated. The TL prime was generated by transposing the letters in positions 2 and 3 (e.g., *bnet*-BENT, *bmip*-BIMP). The RL prime was generated by replacing the letters in positions 2 and 3 (e.g., *bwot*-BENT, *bvup*-BIMP).

Both TL and RL primes contained an illegal onset. Also, the mean position-dependent bigram type frequency (N2_C) of the two types of primes, calculated using the MCWord Database (Medler & Binder, 2005), was matched. For word targets, it was 5.8 for the TL primes and 5.3 for the RL primes, $t(49)=.754$, $p=.454$; for nonword targets, it was 4.7 for the TL primes and 4.8 for the RL primes, $t(49)=-.243$, $p=.809$. Thus, the TL and RL primes were equally (un)pronounceable. The prime-target pairs are listed in the Appendix.[1] In addition to the experimental stimuli, 14 prime-target pairs with similar characteristics served as practice and initial buffer trials.

Fifty prime-target pairs for each type of target (words and nonwords) in two prime type conditions (TL and RL) made a total of 100 trials per participant. Two lists were created with each target word appearing only once within a list, and once in each of the two prime type conditions across the two lists. Half of the participants were assigned to List A, and the other half to List B. The word and nonword targets were presented in separate blocks. To the extent that it is possible to strategically emphasize the lexical and sublexical pathways separately (e.g., Monsell, Patterson, Graham, Hughes, & Milroy, 1992; Reynolds & Besner, 2008, but see Kinoshita & Lupker, 2003; Lupker, Brown, & Colombo, 1997, for an alternative interpretation of the effect of blocking stimulus type), presenting word and nonword targets in separate blocks should maximize pathway control, and therefore increase the opportunity to engage the lexical procedure for words and the sublexical procedure for nonwords. Half of the participants were tested on the word block first, and the other half on the nonword block. The order of trial presentation within blocks and lists was randomized across participants. A short break was administered within each block.

Apparatus and procedure Participants were tested individually, seated approximately 60 cm in front of a flat screen monitor. Stimulus presentation and data recordings were controlled by DMDX software (Forster & Forster, 2003). Verbal responses were recorded by a head-worn microphone. Participants were told that they would see a series of hashes (####) followed by words/nonwords presented in uppercase letters, and that they had to read aloud the words/nonwords as quickly and as accurately as possible. The presence of primes was not mentioned to the participants. Each trial started with the presentation of a forward mask (####) that remained on the screen for 500 ms. The prime was then presented in lowercase letters for 50 ms (five ticks based on the monitor's refresh rate of 10 ms), followed by the target, which was presented in uppercase letters and acted as a backward mask to the prime. The stimuli appeared in black on a white background (10-point Courier New font) and remained on the screen for 2000 ms or until participants responded, whichever happened first.

[1] Due to an oversight, *ldit* was used as an RL prime for both LENT and LUST.

Results

Participants' responses were hand-marked using CheckVocal (Protopapas, 2007). Incorrect responses, mispronunciations, and hesitations (2.5 % of the data) were treated as errors and discarded. To control for temporal dependencies between successive trials, the reaction time (RT) of the previous trial was included in the analyses, so trials whose previous trial corresponded to an error and participants' first trial in each block (4.1 % of the data) were excluded. Extreme outliers (1.1 % of the data) were also identified separately for each participant and removed.

The analyses were performed using linear mixed effects modelling (Baayen, 2008; Baayen, Davidson, & Bates, 2008) and the *languageR* (Baayen, 2008), *lme4* 1.0-5 (Bates, Maechler, Bolker, & Walker, 2013), and *lmerTest* (Kuznetsova, Brockhoff, & Christensen, 2013) packages implemented in R 3.0.2 (2013–09–25, R Core Team, 2013). The linear mixed-effects model we report was created using a backward stepwise model selection procedure. Model comparison was performed using chi-squared log-likelihood ratio tests with maximum likelihood. The Box-Cox procedure indicated that the logarithmic transformation was the optimal transformation to meet the precondition of normality. The model we report included logRT as the dependent variable and as fixed effects the interaction between target type (word vs. nonword) and prime type (TL vs. RL), and the RT of the previous trial (PrevRT). The target type factor and the prime type factor were both deviation-contrast coded (−.5, .5), to reflect the factorial design. Intercepts for subjects and items were included as random effects and so were random slopes for items for the effect of prime type: logRT~target type*prime type+PrevRT + (1 | subject)+(1+prime type | target).

Outliers with a standardized residual greater than 2.5 standard deviations from zero were removed from the fitted model (1.9 % of the data). The results indicated a significant main effect of prime type, so that target reading aloud latencies were significantly faster when the targets were preceded by TL primes compared to RL primes ($t=-5.488$, $p<.001$). Also, there was a main effect of target type, with words being read aloud significantly faster than nonwords ($t=-6.462$, $p<.001$). The effect of the RT of the previous trial was highly significant, $t=14.334$, $p<.001$. Importantly, target type did not interact with prime type ($t<1$). Separate analyses of the word and nonword items showed that the TL priming effect was significant for both (t=−4.118, p<.001, for words, and t=−3.368, p<.01, for nonwords). To test whether the lexical procedure was engaged when word targets were read aloud, Log SUBTLEX frequency was included as a fixed factor in the analysis of the word items. The results showed a significant frequency effect (t=−2.105, p<.05), which suggests that word targets were read aloud via the lexical procedure.[2]

To quantify evidence for the null interaction (see Rouder, Speckman, Sun, Morey & Iverson, 2009), we calculated the Bayes factor using the BayesFactor Package (Version 0.9.7, Morey & Rouder, 2013 available in R) to compare the model we report against the model that did not include the target type by prime type interaction. The model without the interaction term was preferred (the Bayes factor was 13.30653±2.89 %), which according to Jeffreys (1961) provides "strong evidence" for the null hypothesis. That is, the observed TL priming effects do not depend on the lexical status of the target stimulus.

The error analysis was performed using a logit mixed model (Jaeger, 2008) with the target type by prime type interaction as a fixed effect and intercepts for subjects and items as random effects. Similar to the RT analysis, the target type and prime type factors were both deviation-contrast coded (−.5, .5). The results indicated that nonword targets yielded significantly more errors than word targets (z=−3.539, p<.001). Mean RTs (calculated from a total of 2,902 observations) and percentage of errors for each condition are presented in Table 1.

Table 1 Mean reading aloud latencies (reaction times (RTs) in ms) and percent error rates (%E) for each condition

	Word targets			Nonword targets		
	Examples	RTs	%E	Examples	RTs	%E
TL primes	*bnet*-BENT	510	1.0	*bmip*-BIMP	555	4.1
RL primes	*bwot*-BENT	521	1.5	*bvup*-BIMP	567	3.4
TL priming effect		11	.5		12	-.7

TL transposed-letter; *RL* replaced-letter

Discussion

How our reading system codes letter position has been a popular topic of research in the reading domain. The available empirical evidence on the TL priming effect (the finding that *jugde* facilitates the recognition of JUDGE compared to *junpe*), obtained primarily from visual word identification tasks, supports the idea that letter position coding is imprecise, contrary to the assumption of slot-based letter coding schemes. However, to date, no study has investigated TL priming effects in reading aloud nonwords, as well as words. Investigating this issue is important if we are to develop further extant computational models of reading aloud that are able to explain these effects.

In the present study, target words and nonwords yielded equal-sized TL priming effects in reading aloud. This finding mirrors the TL priming effects observed in the same-different task, in which participants decide whether the target word/nonword matches a single referent presented in advance (Kinoshita & Norris, 2009). In that study, TL primes produced almost as much priming as identity primes for both word and nonword targets. To explain the TL priming effects in the same-different task, Kinoshita and Norris (2009) suggested that within the limited time that the prime is available the letter order information is ambiguous, hence TL primes and identity primes are indistinguishable: to the extent that it is uncertain whether the letter *i* comes before or after *m*, *bmip* will match BIMP. To explain the equally robust TL priming effect for words and nonwords, Kinoshita and Norris suggested that the origin of this effect is prelexical. The same pattern of TL priming effects found with word and nonword targets in the present reading aloud task offers additional support for the view that letter position information is ambiguous in the prelexical orthographic representation that serves as input to both the lexical and sublexical procedures for generating phonology.

In addition, our finding is consistent with data from the tachistoscopic identification task (e.g., Adelman, 2011; Gomez et al., 2008), which show that letter identity information is available earlier than precise letter order information (i.e., when presented with ABCDE briefly, and asked to choose between ABCDE and ACBDE, or between ABCDE and AXYDE, participants are more likely to reject AXYDE, which contains wrong letter identity information). Similar to the tachistoscopic identification task, in the reading aloud

[2] Peereman and Content (1997) found that the number of phonographic body neighbors (body neighbors that share the pronunciation of the body, e.g., shrink, ink, mink, are all phonographic body neighbors of "tink") facilitated nonword naming latencies, and interpreted the effect as evidence of lexical influence on nonword reading aloud. Following this line of reasoning, we reanalyzed the nonword naming latencies including the phonographic body N as a covariate (centered to avoid a spurious correlation between the slope and intercept, as per Baayen, 2008, pp. 254-255). Phonographic body N, enumerated based on the Celex word corpus (Baayen, Piepenbrock, & Gulikers, 1995), ranged between 0 and 15, with a mean of 6. Its effect was far from being significant (t=−.814, p=.42), nor did it modulate the size of the TL priming effect (t=.107, p=.92). The TL priming effect remained robust (t=−3.369, p<.01), as did the effect of previous RTs (t=6.7, p<.001). The null effects of the phonographic body N do not support the possibility that the observed TL priming effect with the nonword targets may have been due to the influence of the lexical neighbors.

task, the RL prime *bvup* provides letter identity information that is inconsistent with the target BIMP; hence, the RL prime is more likely to disrupt target reading aloud, yielding slower target reading aloud latencies in this condition compared to the TL priming condition.

The findings from the present study are inconsistent with open bigram models that explain TL priming effects in terms of the greater number of open bigrams shared between the TL prime and the target (e.g., *jugde*-JUDGE) than between the RL prime and the target (e.g., *junpe*-JUDGE). The proponents of these models acknowledge that open bigrams are unsuited to generating serially ordered phoneme representations, and have accordingly suggested that "letter order is encoded more reliably on the sublexical route" (Whitney & Cornelissen, 2008, p.161) and "precise letter order information is required along the fine-grained processing route that generates a sublexical phonological code" (Grainger & Ziegler, 2011, p.5). The present findings are also inconsistent with open bigram models that explain TL priming effects in terms of an orthographic representation that mediates between the letter level and the word level, with open bigrams forming part of the lexical procedure (e.g., Grainger & van Heuven, 2003; Grainger & Ziegler, 2011). Thus, according to open bigram models, TL priming effects should be weak or absent when reading aloud nonwords. This is contradicted by the present data which show robust TL priming effects of equal size for both words and nonwords. In contrast, in the Overlap model (Gomez et al., 2008) and noisy channel model (Norris & Kinoshita, 2012), the uncertainty in the letter order arising from noisy perception, relative to the greater certainty in the letter identity information during the processing of the briefly presented prime is all that is required to explain the TL priming effects observed in the present study.

To summarize, in the present study, TL priming effects of equal size were observed when reading aloud words and nonwords. The observed TL priming effects in the reading aloud task pose a challenge to all available computational models of reading aloud which use a slot-based letter coding scheme. Further, the equal-sized TL priming effects found with words and nonwords suggest that these effects arise at a prelexical level, offering support for the idea that a single orthographic code serves as the input to the lexical and sublexical procedures, and that TL priming effects are due to the uncertainty in the order of letters within this code at the very early stages of the reading process.

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Appendix

Table 2

Table 2 List of experimental word and nonword targets with their corresponding transposed-letter (TL) and replaced-letter (RL) primes

Word targets	TL prime	RL prime	Nonword targets	TL prime	RL prime
BENT	bnet	bwot	BIMP	bmip	bvup
BOND	bnod	bgid	BOMP	bmop	bdep
BUSK	bsuk	bdek	DUNT	dnut	dkot
DUST	dsut	dkit	FUNT	fnut	fkot
FEND	fned	fpud	GUMP	gmup	gdap
FIST	fsit	fgut	HEPT	hpet	hcit
RAMP	rmap	rgup	HUND	hnud	hcod
HUNK	hnuk	hsok	JENT	jnet	jvut
HUNT	hnut	hkot	JOCT	jcot	jdut
JUMP	jmup	jdap	KIFT	kfit	kmut
LEST	lset	lbut	KIST	ksit	kgut
LIFT	lfit	lcat	LESK	lsek	lgik
LIMP	lmip	lvup	LOND	lnod	lgid
LIST	lsit	lgut	MENK	mnek	msak
LUMP	lmup	ldap	MEST	mset	mvut
MEND	mned	mpud	NUCT	ncut	nmit
MINK	mnik	mpek	NUSK	nsuk	ndek
POMP	pmop	pdep	POFT	pfot	pget
REND	rned	rpud	REFT	rfet	rkut
RIFT	rfit	rgut	RISP	rsip	rcap
RUST	rsut	rdit	TINK	tnik	tpek
SOFT	sfot	sget	VUNK	vnuk	vsok
TENT	tnet	tmot	VUST	vsut	vdit
TUSK	tsuk	tdek	ZEMP	zmep	zgup
VEST	vset	vbut	ZISK	zsik	zvok
BEND	bned	bpud	BEFT	bfet	bkut
BUMP	bmup	bdap	BISP	bsip	bcap
BUST	bsut	bdit	DEST	dset	dbut
DUSK	dsuk	dpek	FOCT	fcot	fdut
FOND	fnod	fgid	GUSK	gsuk	gdek
FUNK	fnuk	fsok	HENK	hnek	hsak
RANK	rnak	rgok	HINK	hnik	hpek
HINT	hnit	hgut	JEMP	jmep	jgup
HUMP	hmup	hdap	JUNT	jnut	jkot
JEST	jset	jbat	KOFT	kfot	kget
LEND	lned	lpud	KUST	ksut	kdit
LENT	lnet	ldit	LISK	lsik	lvok
LINK	lnik	lpek	LUNK	lnuk	lsok
LOFT	lfot	lget	MEPT	mpet	mcit
LUST	lsut	ldit	MUNT	mnut	mkot
MIST	msit	mgut	NOMP	nmop	ndep
MUSK	msuk	mdek	NUMP	nmup	ndap
PIMP	pmip	pvup	PIFT	pfit	pjut
RENT	rnet	rdut	RIMP	rmip	rvup
ROMP	rmop	rdep	RUCT	rcut	rpot
RUNT	rnut	rkot	TUND	tnud	tcod
SIFT	sfit	svet	VIST	vsit	vgut

Table 2 (continued)

Word targets	TL prime	RL prime	Nonword targets	TL prime	RL prime
TEND	tned	tpud	VOND	vnod	vgid
TEST	tset	tgut	ZENT	znet	zkut
VENT	vnet	vbit	ZESK	zsek	zgik

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