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Early morphological decomposition during visual word recognition: Evidence from masked transposed-letter priming

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Abstract The present experiments were designed to explore the theory of early morpho-orthographic segmentation (Rastle, Davis, & New, *Psychonomic Bulletin & Review 11*,1090–1098, 2004), which postulates that written words with a true morphologically complex structure (*cleaner*) and those with a morphological pseudostructure (*corner*) are both decomposed into affix and stem morphemes. We used masked complex transposed-letter (TL) nonword primes in a lexical decision task. Experiment 1 replicated the well-known masked TL-priming effect using monomorphemic nonword primes (e.g., *wran–WARN*). Experiment 2 used the same nonword TL stems as in Experiment 1, but combined them with real suffixes (e.g., *ish* as in *wranish–WARN*). Priming was compared with that from nonsuffixed primes in which the real suffixes were replaced with nonmorphemic endings (e.g., *el* as in *wranel–WARN*). Significant priming was found in the suffixed but not in the nonsuffixed condition, suggesting that affix-stripping occurs at prelexical stages in visual word recognition and operates over early letter-position encoding mechanisms.

Keywords Visual word recognition · Masked priming · Morphological processing · Morphological decomposition

How do readers gain access to the orthographic lexical entries of morphologically complex printed words? Three different classes of theory have been proposed. *Full-listing* theories consider the lexicon as a store of full forms, in which lexical representations of morphologically complex words are accessed only by whole-word representations (e.g., Butterworth, 1983; Manelis & Tharp, 1977). *Purely-morphological-access* theories claim that lexical representations of morphologically complex words are accessed only by the representations of the word's constituent morphemes (e.g., Longtin & Meunier, 2005; Rastle, Davis, & New, 2004; Taft & Forster, 1975). And *dual-access* theories postulate that lexical representations of morphologically complex words can be accessed either on the basis of a whole-word representation or by the representations of the word's constituent morphemes (Baayen, Dijkstra, & Schreuder, 1997; Diependaele, Sandra, & Grainger, 2009).

Support for theories positing morphological decomposition has come from unmasked priming, which has demonstrated the influence of morphological structure on word reading (e.g., Diependaele et al., 2009; Marslen-Wilson, Tyler, Waksler, & Older, 1994), but also from masked priming, where recognition of stem targets has been found to be facilitated by prior presentation of morphologically related primes (e.g., Longtin, Segui, & Hallé, 2003; Rastle, Davis, Marslen-Wilson, & Tyler, 2000).

However, debate continues as to the nature of this decomposition process. Some theorists have favoured a morpho-semantic account, in which decomposition occurs only where the meaning of a complex word can be derived from the meaning of its stem morpheme and the syntax of its suffix (e.g., Giraudo & Grainger, 2000, 2001). Others have argued for a purely structural morpho-orthographic decomposition process. For instance, Rastle et al. (2004) used masked priming to compare the priming effects of morphologically related prime–target pairs for which the

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meaning either could be derived from the meaning of its morphemic subunits (*cleaner–CLEAN*) or could not (*corner–CORN*). Priming for both types of words was found, suggesting that morphological decomposition takes place independently of semantic and syntactic constraints. These data indicate that morphological decomposition is based on a prelexical affix-stripping process, first proposed by Taft and Forster (1975), that operates in such a way that every word bearing a true morphological structure (*cleaner*) or a morphological pseudostructure (*corner*) is decomposed.

However, questions about affix-stripping remain that cannot be addressed by the data of Rastle et al. (2004). Given that the primes in the Rastle et al. (2004) study were always words, it cannot be ruled out that affix-stripping is only triggered when a complex letter string *is itself a word*. If affix-stripping depends on purely structural information, morphological priming should occur independently of whether the prime is a real word or a nonword. To distinguish between these two hypotheses, Longtin and Meunier (2005) used a masked priming procedure in which the primes were always nonwords. Their lexical decision study in French compared priming effects on stems of semantically interpretable (*rapidifier–RAPIDE*) and non-interpretable (*sportation–SPORT*) nonword primes, and found similar-sized effects relative to a nonmorphological control, suggesting that morphological decomposition occurs for all morphologically structured items, even if they are not words. Recently, McCormick, Rastle, and Davis (2008, 2009) extended these findings to English by demonstrating that complex words with common orthographic alterations in the stem morpheme (such as a missing "*e*" as in *adorable–ADORE*; McCormick et al., 2008) and morphologically complex nonword primes with orthographic alterations in the stem morpheme (*adorage–ADORE*; McCormick et al., 2009) produced significant priming to the stem target.

Our study aimed to extend these findings to the domain of letter-transpositions, for the purposes of further controlling lexicality and semantic interpretability and locating more precisely the stage of processing at which affix stripping occurs. To further minimize the prime's resemblance to a real word and its semantic interpretability, our nonword primes consisted of stems that were *letter transpositions* of the target words (e.g., *wranish* comprising the transposed-letter [TL] stem *wran* and suffix *-ish*). It is well established that masked TL-nonwords such as the stems used in our study (*wran*) prime their corresponding real-word targets (*warn*) relative to a substituted-letter (SL) control (*whun*; Andrews, 1996; Forster, Davis, Schoknecht, & Carter, 1987; Perea & Lupker, 2003), an effect typically attributed to the uncertainty in position coding in early stages of visual word recognition (e.g., Perea & Lupker, 2004).

No previous study has explored stem target recognition in the context of masked complex TL-nonword priming. If the nonword prime *wranish* facilitates lexical decision to the target word *WARN*, three conclusions could be drawn. Firstly, consistent with the findings of Longtin and Meunier (2005), affix-stripping is triggered automatically and independently of whether or not a word has been activated in the orthographic lexicon, since *wranish* is not a word (and is not a letter-transposition of any word). Secondly, morphologically structured letter strings are decomposed despite little or no semantic relatedness between their constituents. And thirdly, this affix-stripping process occurs very early in word recognition, operating at the same stage as that at which letter position is coded.

We report two experiments. Experiment 1 was designed to replicate the basic TL-priming effect using our materials. Monomorphemic TL-nonwords were presented as primes, followed by the base word of the stem morpheme (e.g., *wran–WARN*), and subjects performed lexical decisions on the target words. From the previous literature, we expected significant priming from TL-nonwords relative to orthographic control primes. Then, in our key Experiment 2, we used the same items as primes as in Experiment 1, but in a morphologically complex form: Stem targets were preceded by suffixed TL-nonword primes (e.g., *wranish–WARN*). Priming was compared with that found in a nonmorphological condition in which primes were created by adding a nonmorphological ending (*el*) to the TL-nonword stem (e.g., *wranel–WARN*). If morphological decomposition is based purely on the early and automatic recognition of an affix, priming should occur in the morphological and not in the nonmorphological condition.

Experiment 1

Method

Subjects A group of 60 undergraduate and graduate students, all native English speakers, participated for course credit or monetary reimbursement.

Materials A total of 36 monomorphemic four- to five-letter-long target words were selected from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993). For each target, we created a TL-nonword prime by transposing the letters in the second and third positions (e.g., wran–WARN). An SL control condition was created, as is typically used in TL-experiments (e.g., Perea & Lupker, 2003), by substituting for the transposed letters (*ra* in *wran*) two new letter identities (e.g., *hu*) in every TL-nonword prime (e.g., *whun–WARN*). A set of 72 nonword targets were extracted from the ARC nonword database (Rastle, Harrington, & Coltheart, 2002). All nonwords were orthographically legal and pronounceable and matched with the word targets on length, position-specific bigram frequency, position-specific trigram frequency, and Coltheart's N. Each nonword target (e.g., *smoob*) was used to create a TL prime (e.g., *somob*) and an SL prime (e.g., *sepob*). The experiment used two testing blocks so that each of the two related primes (i.e., the TL prime and the SL prime) would never appear together. A full list of the stimuli may be downloaded along with this article from www.springerlink.com.

Procedure Stimuli were presented in the centre of a CRT computer screen using the DMDX display system (Forster & Forster, 2003) in randomised order. Each trial consisted of a 500-ms forward mask of hash marks, then a 40-ms prime in lowercase, then the uppercase target stimulus, which appeared in the same position as the hash marks. The target remained on the screen until the subject responded or until 3 s had elapsed. Subjects were instructed to respond as quickly and accurately as possible.

Results and discussion

Word and nonword trials were analysed separately. All of the word trials with incorrect responses (9.8% of the total) were trimmed. No outliers were discarded, since neither standard deviation trimming (discarding RTs above or below 2.0 or 3.0 *SD*s from each subject's mean reading time) nor high and low cutoff trimming (using 300 ms as a low cutoff and 1,500 or 1,300 ms as a high cutoff) changed the size or direction of any of the main effects or interactions. Mean RTs and error rates averaged over subjects are presented in Table 1.

RTs were transformed logarithmically, and the main analyses were performed using the linear mixed-effect model methodology (Baayen, 2008). To reduce the variance in the models, we included trial number as a predictor to measure how far subjects had progressed into the experiment, allowing control for longitudinal task effects such as fatigue or habituation. Furthermore, since every subject saw items in a different random order, trial order may have had different effects on individual subjects. Therefore, to adjust by-subject random slopes for trial number, we included a correlation parameter specified in the random-effect structure of each subject (Baayen, 2008, pp. 251–252). A generalised linear mixed-effects model, as implemented in the lme4 package (from http://cran.r-project.org/web/packages/) for the statistical software R (version 2.10.1; R Development Core Team, 2008), was used, with two fixed-effects factors (Trial Number and Prime Type [TL/SL]) and two random-effects factors (random intercepts for Subjects and Items). These factors were considered separately in a step-wise selection procedure, in the following order: random intercepts for Subjects, random intercepts for Items, Trial Number, by-subject random slopes for Trial Number, Prime Type, Morphological Complexity (Exp. 2 only), and the interaction of Prime Type and Morphological Complexity (Exp. 2 only). Each factor was only included in the mixed-effects model if formal comparisons between models showed a significant improvement of the model's fit when the factor was included. Significance was assessed with p-value sampling via the function pvals.fnc, as implemented in the R language package (Baayen, 2008). The model revealed that words preceded by TL-nonwords were classified significantly faster (13 ms) than were words preceded by SL nonwords, $t = -3.1$, $p = .002$, showing that TL-priming occurs with our particular set of monomorphemic items. The effect of trial number was significant, $t = -3.27$, $p < .001$. The significance of the factor Prime Type did not change when the factor Trial Number was omitted. The mixed-effects analysis of error and nonword data revealed no significant results.

Table 1 Experiment 1: Mean reaction times (in milliseconds) and percentages of errors for real-word targets, averaged across subjects

Condition	Reaction times	Error Rates	Example
TL	525 (75)	9.2 (7.6)	wran–WARN
SL	538 (72)	10.4 (8.7)	whun–WARN
TL effect	13	1.2	

Standard deviations are shown in parentheses. TL, transposed letters; SL, substituted letters

Thus, Experiment 1 successfully replicated the previously reported masked TL-priming effect using our own materials.

Experiment 2

Method

Subjects A group of 120 undergraduate and graduate students, all native English speakers, participated in this study for course credit or monetary reimbursement.

Materials The same targets were used as in the suffixed and nonsuffixed conditions of Experiment 1. Primes in the suffixed condition were created by adding a real suffix to the stem (e.g., *wranish*/*whunish*), whereas primes in the nonsuffixed condition were created by adding a nonmorphological ending (e.g., *wranel*/*whunel*). To avoid effects ascribed to the base word of the whole prime, we selected stem and affix combinations in such a way as to ensure that the entire prime was not a letter-transposition of any real word (as in *wraned*/*warned*). Both TL conditions were matched with their corresponding set of control items on length, consonant–vowel structure, position-specific bigram frequency, and position-specific trigram frequency. A full list of the stimuli may be downloaded from www.springerlink.com.

The nonword targets from Experiment 1 and the same morphemic and nonmorphemic endings used to create nonword primes in the Experiment 1 word trials were used to create the nonword trials (e.g., *somobful*/*sepobful*). Four different lists were created using a Latin square design and tested with different subject groups.

Procedure The same procedure was used as in Experiment 1.

Results and discussion

Word and nonword trials were analysed separately. All word trials with incorrect responses (8.1% of the total) were trimmed. As in Experiment 1, no outliers were discarded, because the analysis of the trimmed data did not change the size or the directions of the main effects and interactions. Mean RTs and error rates were analysed following the procedures of Experiment 1 and are presented in Table 2.

Similarly to Experiment 1, a mixed-effects model analysis of log RT data was carried out, with four fixed-effect factors (Trial Number, Morphological Complexity [suffixed/nonsuffixed], Prime Type [TL/SL], and the interaction between Morphological Complexity and Prime Type) and two random-effects factors (random intercepts for Subjects and Items). As in Experiment 1, trial number was included as a predictor. The model revealed a significant main linear effect of prime type, $t = -3.1$, $p = .003$. The main effect of morphological complexity was not significant, $t = 0.3$, $p = .757$. The interaction of prime type and morphological complexity indicated that TL facilitation occurred in the suffixed but not in the nonsuffixed condition, $t = 2.4$, $p = .017$.

Table 2 Experiment 2: Mean reaction times (in milliseconds) and percentages of errors for real-word targets, averaged across subjects

Condition	Reaction Times	Error Rates	Example
Suffixed			
TL	555 (91)	7.9 (11.5)	wranish–WARN
SL	571 (103)	8.4 (11.7)	whunish–WARN
TL effect	16	0.5	
Nonsuffixed			
TL	571 (97)	7.1 (11)	wranel–WARN
SL	567 (85)	9.1 (11.9)	whunel–WARN
TL effect	–4	2.0	

Standard deviations are shown in parentheses. TL, transposed letters; SL, substituted letters

In addition, the suffixed and nonsuffixed data sets were fitted to two separate linear models with two fixed-effect factors (Trial Number and Prime Type [TL/SL]) and two random-effect factors (random intercepts for Subjects and Items). The suffixed data showed a significant linear effect of prime type, $t = -3.0$, $p = .003$ (less than the Bonferroni-corrected value); words preceded by suffixed TL-nonwords were responded to 16 ms faster than were words preceded by suffixed SL nonwords. The effect of trial number was not significant, $t = -1.1$, $p = .252$. In the nonsuffixed data, the effect of trial number was also nonsignificant, $t = -2.2$, $p = .031$ (greater than the Bonferroni-corrected value). The effect of prime type was not significant, $t = 0.3$, $p = .764$.

The significance of the obtained results did not change when the factor Trial Number was omitted. None of the error data and nonword data effects were significant.

The degree of orthographic overlap between a subset of the TL primes with an existing suffixed letter string (e.g., *wranish* overlaps with *warning*) did not significantly correlate with the TL-priming effect ($r = .073$, $t = 0.6$, $p = .540$). Moreover, to explore whether there was a relationship between TL-priming and position-specific bigram frequency, the length of final letter sequences (*el*, *ish*, etc.), or the position-specific boundary bigram frequency of the bigrams at morpheme boundaries (e.g., *ni* in *wranish*), we entered these as correlation variables. The difference between the suffixed and nonsuffixed TL-priming effect did not correlate significantly with position-specific bigram frequency ($r = .047$, $t = 0.4$, $p = .693$) or length of the final letter sequences ($r = .080$, $t = 0.7$, $p = .504$), nor with position-specific boundary bigram frequency ($r = .003$, $t = 0.03$, $p = .978$).

The finding that the masked presentation of a suffixed TL-nonword facilitates the recognition of the base word of the stem morpheme (*wranish–WARN*), whereas nonsuffixed TL-nonword primes (*wranel–WARN*) do not, shows that priming cannot be attributed to simple orthographic overlap and provides evidence in support of a theory of visual word recognition in which prelexical morphological decomposition operates over early letter-position encoding mechanisms. Most critically, the data extend Longtin and Meunier's (2005) and McCormick et al.'s (2009) results to the domain of TL-priming effects, providing evidence for affix-stripping in the absence of semantic relatedness.

General discussion

The transposed-letter priming effect obtained in Experiment 2 can only be explained in terms of morphological decomposition, since priming of the target WARN by the prime *wranish* could only be achieved if there is a mechanism that isolates the stem of a prime at very early stages in visual word recognition. The present data are thus inconsistent with full-listing accounts (e.g., Butterworth, 1983; Manelis & Tharp, 1977) that reject the decomposition hypothesis. Our results are also incompatible with purely postlexical accounts of morphological decomposition, which assume that access to morphemic subunits does not occur until after whole-word representations have been accessed (Giraudo & Grainger, 2001, 2003). Because those models postulate that only existing morphologically complex words are decomposed, nonwords such as those in our present experiments would be rejected by the word recognition system, and therefore not decomposed. However, although our findings provide evidence against postlexical decomposition accounts, they do not rule out models allowing two parallel access routes (Baayen et al., 1997; Caramazza, Laudanna, & Romani, 1988; Diependaele et al., 2009)—a decompositional route and a full-form route—or models proposing morphological segmentation at the level of lemmas (e.g., Crepaldi, Rastle, Coltheart, & Nickels, 2010).

Our data are consistent with previous findings that decomposition of morphologically structured items occurs in the presence of an affix, independently of whether the affix is a subconstituent of a true morphological structure (*cleaner–CLEAN*), a morphological pseudostructure (e.g., *corner*; Rastle et al., 2004), or a morphologically structured nonword (*quickify–QUICK, sportation–SPORT*: Longtin & Meunier, 2005; *adorage–ADORE*: McCormick et al., 2009). Our data extend these findings to the TL priming domain, showing TL-priming in the context of morphologically structured TL-nonword primes (*wranish–WARN*). All TL-nonword primes used in the morphological condition of Experiment 2 were meaningless: For example, the combination of the TL-nonword *wran* or its corresponding base word *warn* with the suffix *-ish* resulted in a meaningless letter string (*wranish* or *warnish*). This lack of meaning minimized the possibility that the priming effects were driven by semantic relationships between prime and target. Morphological decomposition instead appears to be triggered purely by the presence of affixes, allowing for fast and automatic access to the internal structure of words.

Affix representations can be thought of as a strongly memorized list of highly productive morphological subunits that can be accessed at very early stages of visual word processing. A letter chunk that successfully matches an affix representation (e.g., *-ish* in *wranish*) is rapidly identified while the word recognition system continues searching for deeper lexical structures throughout the rest of the letter string. After affix-stripping, the remaining letter string *wran* activates (with positional uncertainty) the representation of *warn*, producing priming. Nonmorphemic endings such as *el* as in *wranel*, however, are not memorized in the same manner and are not used as triggers to detect morpho-orthographic substructures; therefore, affix-stripping fails, and no priming occurs.

One alternative possibility is that the effects obtained here were driven by lower-level orthographic stimulus features, such as the frequency or length of the final letter sequences or the frequency of morpheme boundary bigrams. A difference between suffixed and nonsuffixed items on these factors could potentially influence priming by affecting the ease with which stem morphemes can be activated in the lexicon. However, there was no relationship between TL-priming and position-specific bigram frequency, the length of morphemic or nonmorphemic endings, or position-specific boundary bigram frequency, which would appear to rule out such an account.

Given that the wranish–WARN effect cannot be attributed to low-level features of the prime or semantic overlap between prime and target, we conclude that the observed priming constitutes a morphological effect. Our studies suggest that affix-stripping is triggered by a mechanism operating at very early orthographic processing stages, while letter-position coding is not yet fully resolved, showing that morphemic structure and letter position are coded at the same stage, prior to lexical access. These findings thus have implications for theories of letter-position coding (Davis, 2010; Whitney, 2001) suggesting that the encoding of letter identity and letter position may embody knowledge of morphemic structure. That is, orthographic analysis does not uniquely rely on the coding of lower-level visual processing features, because higher-level linguistic factors appear to be taken into account at the same time. However, many questions still remain to be answered. For example, we note that other findings in relation to morpho-orthographic decomposition, such as the reported absence of priming when TL manipulations occur across morpheme boundaries (e.g., *clea**en**r*) as opposed to within them (e.g., *c**el**aner*; Christianson, Johnson, & Rayner, 2005; Duñabeitia, Perea, & Carreiras, 2007), would seem to rely on affix-stripping drawing on precise letter-position information and occurring after letter-position encoding has been resolved. Further research is needed to reveal the precise relationship between letter position coding and affix-stripping.

Our account above further predicts that primes like *wransih* should also produce priming to the target *WARN*, relative to an orthographic control. However such effects may not be as strong, since the decoding of TL affixes might conflict with the lesser degrees of positional uncertainty at the word's ends (Perea & Lupker, 2007).

Future investigations could explore the extent to which positional imprecision can be tolerated, and if this can also be extended to affixal units.

In summary, the present experiments suggest that affix representations are matched with input letter strings independently of their lexical and semantic context, allowing for fast decomposition of affixed words or nonwords, even in the presence of letter-transpositions. This finding thus confirms previous evidence that affix-stripping operates over early orthographic encoding mechanisms and allows us to locate morphological decomposition temporally at very early, semantically "blind", prelexical stages of word recognition.

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