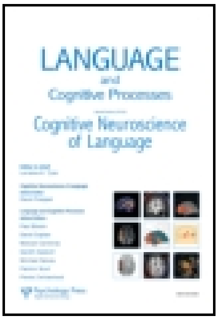


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# Morphological decomposition and the transposed-letter (TL) position effect

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# Morphological decomposition and the transposed-letter (TL) position effect

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When a nonword is created from a real word by transposing two medial letters (e.g., *oeby* from *obey*), the former is confused with the latter more than when the transposition involves the initial letter (e.g., *boey*). This is called the "transposed-letter (TL) Position" effect. It is shown here that the addition of a prefix eliminates the TL Position effect (i.e., *disboey* shows as much interference as *disoeby* relative to a nontransposed control). The TL Position effect also disappears if the prefix creates a nonword when added to the stem (e.g., *reboey* shows as much interference as *reoeby*), but there is no interference at all when a nonprefix is added to the stem instead (e.g., *raboey* or *raoeby*). The fact that there is strong TL interference for prefixed nonwords (e.g., *reboey* and *reoeby*) strongly points to unavoidable morphological decomposition. The disappearance of the TL Position effect when a prefix is added to the stem is ascribed to the reduction in perceptual salience for the initial letter, and this is confirmed when the TL Position was also shown to disappear when the prefix was replaced by digits. The results of the five experiments lead to a consideration of the way in which models of orthographic processing might handle both TL interference and morphological decomposition.

***Keywords:*** Morphological decomposition; Transposed letters; Letter position; Prefixed words.



It has been amply demonstrated that the lexical representation of a word can be activated even when two of its letters have been transposed, hence demonstrating that the encoding of letter position is not precise. For example, a "transposed-letter" (TL) nonword (e.g., *oeby,* generated from *obey*) is harder to reject as a word in a lexical decision task than a "replaced-letter" (RL) nonword (e.g., *ouhy*) that is created by substituting other letters for the transposed ones (e.g., Andrews, 1996; Chambers, 1979; Frankish & Turner, 2007; Lee & Taft, 2009, 2011; O'Connor & Forster, 1981; Perea & Lupker, 2004). Another line of evidence that letter position is imprecisely encoded is the facilitation of response times to a target word arising from the masked

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presentation of a TL version of that word. Recognition of *OBEY*,[1] for example, is faster after the masked presentation of *oeby* in comparison to *ouhy* (e.g., Forster, Davis, Schoknecht, & Carter, 1987; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2004; Schoonbaert & Grainger, 2004).

While various theoretical explanations have been given for these TL effects (e.g., Davis, 2010; Gómez, Ratcliff, & Perea, 2008; Grainger & van Heuven, 2003; Grainger & Ziegler, 2011; Lee & Taft, 2009, 2011; Norris, Kinoshita, & van Casteren, 2010; Whitney, 2001; Whitney & Cornelissen, 2005, 2008), all accounts are based on the assumption that the effects reflect the mechanisms involved in early stages of orthographic processing whereby the letters of a word are used to activate the representation of that word in lexical memory. In some accounts (e.g., Grainger & van Heuven, 2003, Grainger & Ziegler, 2011; Whitney, 2001; Whitney & Cornelissen, 2005, 2008), there is a level of processing that incorporates "open" bigrams (i.e., adjacent and nonadjacent ordered pairs of letters), and TL effects arise from the overlap between the open bigrams contained in the stimulus and those of the base word (such as the *ob*, *by*, and *ey* of both *oeby* and *obey*). Spatial coding accounts (e.g., Davis, 2010) explain TL effects in terms of letters generating a pattern of activation of decreasing strength in correspondence to their relative position. It is the similarity between this spatially based coding for a TL stimulus and the coding expected for its base-word that gives rise to the effects. Other accounts ascribe TL effects to the imprecise tuning of letters to their positional slots (e.g., Gómez et al., 2008; Norris et al., 2010), so that the representation of the *b* of *obey* is most responsive to the appearance of that letter in the second position of the letter-string, but also partially responsive to its appearance in the third position. Finally, Lee and Taft (2009, 2011) propose that letters are tried out in different subsyllabic slots (corresponding to onsets, vowels, and codas), until a lexical representation is successfully activated. When transposed letters are tried out in the slots that activate the base-word, TL effects will emerge.

The main focus of this paper is to examine the relationship between the processing of letter position and morphology. Models that handle TL effects have largely ignored the issue of morphological analysis, but the experiments to be reported here lead to a consideration of how morphology might be incorporated into such models. In fact, a number of previous studies have employed the TL effect as a technique to identify the locus of morphological processing.

The most common approach to this issue has been to examine whether transposition across a morpheme boundary is more disruptive to the recognition of a polymorphemic word than transposition within a morpheme. Early and obligatory morphological decomposition (e.g., Longtin, Segui, & Halle, 2003; Rastle & Davis, 2008; Taft, 2004; Taft & Forster, 1975) would be supported if cross-morphemic transpositions were more disruptive than intra-morphemic transpositions (as seen, for example, in weaker masked priming of the base-word). That is, transposition within the affix makes it hard to identify for the purpose of decomposition. For example, if *hoarder* is recognised only after the suffix *er* has been isolated from the stem *hoard*, then disturbance of that suffix should impede recognition. Hence, *hoaredr* might not prime *HOARDER* to the same extent that *hoadrer* does, where *er* is intact. However, the studies that have looked at this issue have obtained quite inconsistent results.

[1] In masked priming experiments, the target is presented in uppercase and the prime in lowercase. The same principle will be followed here when giving examples (albeit using italics to differentiate the example from the text).

Christianson, Johnson, and Rayner (2005) found negligible priming of English-derived words when the transposition within the prime crossed the morpheme boundary (e.g., *hoaredr-HOARDER*), while pseudo-derived words with nonexisting stems did show priming (e.g., *saunetr-SAUNTER*). Testing both Basque and Spanish affixed words, Duñabeitia, Perea, and Carreiras (2007) also failed to observe priming for cross-morphemic transpositions and, further, showed that an intra-morphemic transformation did produce priming (e.g., *hoadrer-HOARDER*). In marked contrast, however, Rueckl and Rimzhim (2011) found masked priming effects of the same magnitude for both cross- and intra-morphemic transpositions in English, hence throwing doubt on the claims made about affix disruption. They not only found cross-morphemic TL priming of the derived word, but also priming when the target was the stem alone (e.g., *hoaredr-HOARD*), as reported by Grainger and Ziegler (2011) as well.

The difference in TL priming shown by Christianson et al. (2005) between truly affixed words (like *HOARDER*) and orthographically similar nonaffixed words (like *SAUNTER*) indicates that the latter are activated directly from letter information without the mediation of decomposition. This implies that decomposition is not blindly triggered by the existence of an orthographic structure that merely looks like an affix. Such a result might therefore be taken to support whole-word access over obligatory decomposition. However, such a conclusion appears to be in conflict with the fact that pseudo-affixed words like *corner* have been shown to prime their pseudo-stem (*CORN*) in the masked priming paradigm (e.g., Longtin et al., 2003; Rastle & Davis, 2008), a result that indicates that letters that look like affixes are indeed inappropriately stripped off at the early stages of processing. To resolve this apparent conflict, it should be noted that pseudo-affixed words must ultimately be recognised through a whole-word representation even if inappropriate decomposition takes place initially. Disruption of the pseudo-suffix through transposition should not prevent that whole-word representation being activated, which is why strong priming for *saunetr-SAUNTER* can still occur despite the existence of blind, obligatory decomposition.

The failure to find cross-morphemic TL priming when the affix is disrupted (Christianson et al., 2005; Duñabeitia et al., 2007) has been taken to support the idea that derived words are only accessible when their stem can be isolated from an identifiable affix (i.e., obligatory decomposition). However, it is not the case that obligatory decomposition is ruled out by the existence of cross-morphemic TL priming (e.g., Grainger & Ziegler, 2011; Rueckl & Rimzhim, 2011). It could simply be that the assignment of letters to their position in the word is imprecisely encoded (e.g., Gómez et al., 2008) such that the *e* of *hoaredr* is most strongly slotted into the third last position, but more weakly slotted into the second last position (and vice versa for the *d*). In this way, the morphological representations of *er* and *hoard* can be activated to a sufficient level for priming of *HOARDER* to occur via decomposition despite both components being disrupted. Thus, aside from the inconsistency of the experimental results *per se*, the fact that both the existence and nonexistence of priming can be interpreted within the same account means that cross-morphemic TL effects may not be the most informative way to examine morphological processing.

Another way in which TL effects have been used to examine morphological decomposition is where the masked prime has two letters transposed within the stem of a nonword composed of a real word combined with an inappropriate affix (e.g., *wranish* from the nonword *warnish* composed of *warn* and *ish*). Using such TL primes, Beyersmann, Castles, and Coltheart (2011) observed faster lexical decision times to the real-word stems (e.g., *wranish-WARN*) relative to RL control primes (e.g., *whunish-WARN*) and, importantly, no such priming was observed when the affix was replaced with a nonaffix (e.g., *wranel-WARN*). It seems that such a result can only be explained in terms of morpheme-based decomposition (though see Beyersmann, Duñabeitia, Carreiras, Coltheart, & Castles, 2012, for contradictory results in Spanish).

The present study adopts a different starting point. It is well established (e.g., Bruner & O'Dowd, 1958; Chambers, 1979; Gómez et al., 2008; Kinoshita, Castles, & Davis, 2009; Perea & Lupker, 2003; Rayner, White, Johnson, & Liversedge, 2006; White, Johnson, Liversedge, & Rayner, 2008) that transpositions involving the initial letter of a word are less able to activate the base-word than those involving medial letters (though Schoonbaert and Grainger, 2004, only found a significant difference for words of less than seven letters). This differential impact of initial and medial transpositions will be referred to as the "TL Position" effect. For example, lexical decision responses to the medial TL nonword *oeby* have been shown to produce greater confusion with the base-word *obey* than lexical decision responses to the initial TL nonword *boey* (e.g., Chambers, 1979). It is apparent that the initial letter of a word provides critical information about word identity such that its disruption makes it hard to activate the lexical representation for that word.

This fact can be potentially used to evaluate whether a prefixed word is recognised through a lexical representation of its stem after the prefix has been stripped off (e.g., Taft & Ardasinski, 2006; Taft & Forster, 1975). If isolation of the stem through prefix stripping is indeed the pathway to recognition, one might suppose that the addition of a prefix to the base-word (e.g., *disobey*) will have no impact on the TL Position effect. That is, if the prefix *dis* is stripped off in order to recognise *disobey*, disruption of the critical initial letter of the remaining stem *obey* should make it difficult to access the base-word. Hence, *disboey* should show less interference relative to the RL baseline than should *disoeby*, even though both now involve a medial transposition.

In order to examine this idea, the first step is to demonstrate the existence of the basic TL Position effect with a set of words that can be subsequently tested with the addition of a prefix.



## EXPERIMENT 1: UNPREFIXED ITEMS

The purpose of Experiment 1 was to replicate the finding of Chambers (1979) that medial transpositions (e.g., *oeby*) lead to stronger interference in nonword classification than initial transpositions (e.g., *boey*). If this TL Position effect were demonstrated, an examination could then be made as to whether the same effect was obtained when a prefix was added.

### Method

#### *Materials*

Forty-two words of four to seven letters in length (mean = 5.45, $SD = 0.74$) were selected on the grounds that each could be used as the stem of a transparently prefixed word (e.g., *obey*, *worthy*, *trust*, *sense*, which are the stems of *disobey*, *unworthy*, *mistrust*, *nonsense* respectively). The mean frequency of these stem words was 161.75 occurrences per million ($SD = 361.04$) according to the CELEX word frequency database (Baayen, Piepenbrock, & van Rijn, 1993). Three experimental nonword conditions were formed by modifying these 42 words in different ways. A "Medial TL" condition was formed by transposing the second and third letters of the base-word (e.g., *oeby*, *wrothy*, *turst*, *snese*), while an "Initial TL" condition had the first and second letters transposed (e.g., *boey*, *owrthy*, *rtust*, *esnse*). The baseline control items involved a replacement of letters rather than transposition. In this "RL Control" condition, the first three letters of the base-word were substituted so that the nonword items had as many different letters to the Initial TL condition as they had to the Medial TL condition (e.g., *tuay*, *arfthy*, *lfust*, *omrse*).[2] Because the two TL conditions were compared to a single RL Control condition, a decision had to be made as to which of the two should more closely match the control on consonant-vowel (CV) structure. Given that the focus was primarily on the relative magnitude of interference in the Initial TL condition, it was the CV structure of this condition that was used as the framework for the RL Controls. The three conditions were matched overall on the number of words differing by one substituted letter (i.e., neighbourhood size or "N"), the number of words having one less or one more letter ("sub" and "super" sets), and bigram frequency (all $t$'s $< 1$). All of the items are presented in the Appendix, along with a table showing the values for N, sub and super-sets, and bigram frequency for each condition.

These 42 items were set up within a Latin-Square design so that all participants were exposed to all conditions, but no participant saw more than one member of each triplet generated from the same base-word. Thus, three sublists were formed with 14 items in each condition producing a mixed factorial design with Condition (Medial TL, Initial TL, Control) as the within-participants and within-items factor, and Sublist (sublists 1, 2, and 3) as the between-participants and between-items factor. However, any effect of Sublist would be meaningless, since it would arise solely from the particular assignment of items to a sublist and, therefore, the results for that factor will not be reported.

The same set of real-word distractors was used in all three sublists and consisted of 42 nonprefixed words whose frequencies largely overlapped with those of the base-words of the TL items and which were of the same mean length as the nonword targets (e.g., *cent*, *apron*, *beauty*, *usual*). There were also 12 practice items composed of words and nonwords of a similar type to those used in the experiment.

### *Participants*

The participants were 42 undergraduate psychology students from the University of New South who received course credit for participating. All were monolingual English speakers with normal or corrected-to-normal vision. They were randomly allocated to one of the three sublists, with 14 participants per sublist.

### *Procedure*

The DMDX computer display program (Forster & Forster, 2003) was used to administer the lexical decision task. Each item was presented in lowercase for 250 ms in 20 point Arial font. There was a 2,000 ms delay between the response and the next item being presented. Participants were tested individually in a quiet room. They were

[2] The RL Control items used in previous experiments typically change one or both of the transposed letters of the TL condition rather than three letters. However, there is no obvious reason to think that the three-letter substitution would have had any impact on the conclusions that are drawn from the experiments to be reported. The different experiments show differential effects of TL despite the control items being constructed in the same way.

told that a series of letter-strings would appear on the computer screen, and that they should press the right shift key if it was a real English word, or the left shift key if it was not. They were instructed to respond as quickly but as accurately as possible.

## Results and discussion

After any response over 2,000 ms was eliminated (only 1 response), cut-off values for each participant were calculated for response times as two standard deviations above or below the mean across all correct "no" responses, and any outlying values were replaced by the relevant cut-off value (5% of responses). Two triplets of items were removed from the item analysis of reaction times (RT) owing to error rates (ER) of 50% or more for at least one member of the triplet. With such a high error rate, RT becomes an unreliable measure, being based on too few responses. The mean RTs and ER for each condition can be found in Table 1.

A clear TL Position effect was observed on both the speed and accuracy measures: The Medial TL condition was significantly slower than the Initial TL condition, $F_1(1,39) = 17.74$, $MSE = 1{,}382.04$, $p < .001$; $F_2(1,37) = 12.83$, $MSE = 1{,}929.60$, $p < .001$, as well as significantly more error-prone, $F_1$ $(1,39) = 25.71$, $MSE = 43.92$, $p < .001$; $F_2(1,39) = 5.70$, $MSE = 196.66$, $p < .05$. In fact, the Initial TL condition showed only weak interference when compared to the RL Control, with only the participant analysis of RT showing more than a trend, $F_1$ $(1,39) = 6.12$, $MSE = 1{,}168.70$, $p < .02$; $F_2(1,37) = 3.22$, $MSE = 1{,}736.98$, $p < .1$ for RT, and $F_1$ $(1,39) = 3.45$, $MSE = 30.26$, $p < .1$; $F_2(1,39) = 1.74$, $MSE = 61.66$, $p > .1$ for ER. In contrast, the Medial TL condition showed highly significant interference relative to the RL baseline, $F_1(1,39) = 39.59$, $MSE = 1{,}468.67$, $p < .001$; $F_2(1,37) = 20.63$, $MSE = 2{,}611.73$, $p < .001$ for RT, and $F_1(1,39) = 45.31$, $MSE = 42.40$, $p < .001$; $F_2(1,39) = 12.10$, $MSE = 158.80$, $p < .001$ for ER.

The results reveal a clear TL Position effect, with far greater confusion with the base-word when two internal letters are transposed than when the initial letter is disrupted through transposition. In fact, transposition of the initial letters failed to generate significant interference relative to the RL Control implying that the base-word was barely activated at all. The question can now be addressed whether the same is true when a prefix is appended to the TL nonword even though the Initial TL items (e.g., *disboey*) now have an internal transformation.

TABLE 1

Mean lexical decision times (RT in ms) and % error rates (ER) based on the participant analysis for the unprefixed items of Experiment 1. The transposed-letter (TL) Position effect is the difference between the Medial and Initial TL conditions. Initial and Medial interference is measured relative to the replaced-letter (RL) Control

| *Condition* | *Example* | *RT* | *ER* |
|---|---|---|---|
| Medial TL | *oeby* | 678 | 13.30 |
| Initial TL | *boey* | 644 | 5.96 |
| RL Control | *tuay* | 625 | 3.73 |
| TL Position effect | | +34 | +7.34 |
| Initial interference | | +19 | +2.23 |
| Medial interference | | +53 | +9.57 |

# EXPERIMENT 2: PREFIXED ITEMS

## Method

### Materials and procedure

The 42 items used in Experiment 1 were presented in Experiment 2 with a prefix that combined with the base-word of the stem to form a real prefixed word (e.g., *disobey*, *unworthy*, *mistrust*, *nonsense*). The same three conditions were used, but with the prefix attached: Medial TL (e.g., *disoeby*, *unwrothy*, *misturst*, *nonsnese*), Initial TL (e.g., *disboey, unowrthy*, *misrtust*, *nonesnse*), and RL Control (e.g., *distuay, unarfthy*, *mislfust*, *nonomrse*). The mean length of the prefix was 2.36 letters ($SD = 0.49$), and the mean frequency of the prefixed base-words was 6.32 occurrences per million ($SD = 7.99$) according to Baayen et al. (1993). The prefixes used with each stem can be found in the Appendix along with the stimulus characteristics for each condition.

The real-word distractors required for the lexical decision task were 42 prefixed words that had a similar distribution of prefixes and were of the same mean length as the nonword targets, as well as having a range of frequencies that largely overlapped with that of the base-words (e.g., *disarray*, *unsure*, *mistreat*, *nonfiction*). The stem was not a word in its own right for 10 of these distractors (e.g., *unkempt*, *distort*, *invader*). As in Experiment 1, a Latin-Square design was used with three different sublists and the same set of distractors in each sublist. The experimental procedure was also identical to that of Experiment 1.

### Participants

A new set of 30 participants were recruited from the same pool as Experiment 1. They were randomly allocated to one of the three sublists, with 10 participants per sublist.

## Results and discussion

Nine responses exceeded the 2,000 ms acceptance criterion, while the replacement cut-off was used for 3% of responses. The error rate was generally high in this experiment and the RT analysis was therefore potentially compromised by having to remove both participants and items that had a mean RT for at least one condition that was based on 50% or fewer responses. By this criterion, nine participants were excluded from the participant RT analysis (but not the error analysis), and 14 triplets of items were removed from the item RT analysis (but not the error analysis). The resulting mean RT and ER for each condition can be found in Table 2.

It was apparent from the results that the TL Position effect disappeared in this experiment. Not only was there no difference at all between the Initial and Medial TL conditions in either speed or accuracy, all $F$'s $< 1.06$, but the former showed highly significant interference relative to the RL Control condition for both RT, $F_1(1,18) = 20.73$, $MSE = 3{,}388.66$, $p < .001$; $F_2(1,25) = 22.25$, $MSE = 4{,}240.69$, $p < .001$, and accuracy, $F_1(1,27) = 122.36$, $MSE = 70.30$, $p < .001$; $F_2(1,39) = 32.68$, $MSE = 390.25$, $p < .001$. The difference between the Medial TL and RL Control conditions was also highly significant, $F_1(1,18) = 28.25$, $MSE = 3{,}090.55$, $p < .001$; $F_2(1,25) = 17.03$, $MSE = 5{,}333.89$, $p < .001$ for RT, and $F_1(1,27) = 87.46$, $MSE = 128.50$, $p < .001$; $F_2(1,39) = 81.31$, $MSE = 207.20$, $p < .001$ for ER.

The purpose of this experiment was to establish whether the strong TL interference effect that is typically seen when the internal letters of a word are transposed is lost

TABLE 2

Mean lexical decision times (RT in ms) and % error rates (ER) based on the participant analysis for the prefixed items of Experiment 2. The transposed-letter (TL) Position effect is the difference between the Medial and Initial TL conditions. Initial and Medial interference is measured relative to the replaced-letter (RL) Control

| *Condition* | *Example* | *RT* | *ER* |
|---|---|---|---|
| Medial TL | *disoeby* | 821 | 34.66 |
| Initial TL | *disboey* | 811 | 31.24 |
| RL Control | *distuay* | 728 | 7.29 |
| TL Position effect | | +10 | +3.42 |
| Initial interference | | +83 | +23.95 |
| Medial interference | | +93 | +27.37 |

when those internal letters form the initial part of the stem of the word. If *disobey* is recognised only through a representation of its stem *obey* after the prefix *dis* has been stripped off, then the weakened activation of that stem through disruption of its initial letters (e.g., *boey*) might have been expected to minimise the TL interference effect. This was not the case. The amount of TL interference was just as strong as when the transposition was of letters internal to the stem (as in *disoeby*). The interference arising for the Initial TL condition on the RT measure was found despite the reduction in power arising from the exclusion of a high number of participants and items owing to high ER.

On the surface at least, the results of this experiment might be taken to mean that prefixed words are treated as whole-words in the lexicon and not necessarily accessed through decomposition (e.g., Baayen, Dijkstra, & Schreuder, 1997; Bertram, Schreuder, & Baayen, 2000; Schreuder & Baayen, 1995). They are also consistent with the dual-route approach to orthographic processing put forward by Grainger and Ziegler (2011) where TL effects arise from a coarse-grained orthographic analysis, while morphological decomposition occurs within a separate fine-grained orthographic analysis that codes letter position precisely. Orthographic representations of whole affixed words exist and these are accessed through the coarse-grained system and, hence, are subject to standard TL effects. Thus, disruption of the stem of the prefixed word through transposition will be just as strong whether it is stem-initial or stem-medial, because both are word-medial transpositions when considering the prefixed word as a whole. Although the stem of a prefixed word will be accessed through the fine-grained system after decomposition, that pathway is not subject to TL effects.

It would be premature, however, to draw the above conclusion that the results of Experiment 2 support whole-word access over decomposition because the assumption made about the source of the TL Position effect may have been misguided. The experiment was motivated by the idea that initial letters are more important than medial letters because a lexical representation is more sensitive to information about its beginning than its middle, capitalising on the fact that the former enters the processing system earlier than the latter. Therefore, if a prefixed word is recognised through the lexical representation for its stem, the initial letter of that stem should be more important for its recognition than its medial letters. However, there is an alternative way to explain the priority of the initial letter in activating lexical information, and that is simply that the initial letter is physically more salient than any medial letter. That is, medial letters are subject to lateral masking (e.g., Townsend, Taylor, & Brown, 1971; Wolford & Hollingsworth, 1974), while the space before the initial letter makes its identity and position in the letter-string easy to process.

The relative ease of processing the position of the initial letter is a feature of most recent models of letter-position processing (e.g., Davis, 2010; Gómez et al., 2008; Grainger & van Heuven, 2003; Lee & Taft, 2009, 2011; Whitney, 2001), even if it is instantiated differently in the different accounts. In the model of Whitney (2001) and Whitney and Cornelissen (2005, 2008), the initial letter is most quickly activated because it receives the strongest input from the feature level. In the spatial coding model of Davis (2010), there is a bank of activation nodes that is specialised to respond to the initial letter, while Gómez et al. (2008) suggest that the initial letter slot is more tightly tuned than the medial slots. According to Lee and Taft (2009, 2011), the perceptual prominence of the onset position allows the initial consonant to be easily assigned to its onset slot at an early stage of subsyllabic analysis.

If the TL Position effect does indeed arise at a perceptual level, its existence cannot be used as a diagnostic for whether a prefixed word is recognised through its stem rather than through a whole-word representation. That is, the logic behind Experiment 2 can be questioned. Following on from Experiment 2, however, it is still possible to examine TL interference as a test of the idea that prefixes are automatically stripped off.

Beyersmann et al. (2011) demonstrated facilitation when the prime was a transposed version of the target along with an inappropriate suffix (e.g., *wranish-WARN*), and not when there was a nonsuffix added (e.g., *wranel-WARN*). Although looking at suffixed rather than prefixed items (and contradicted by results from Beyersmann et al., 2012, in Spanish), such a result shows that TL effects can emerge even when the base-item is not a word (e.g., *warnish*), and this provides the basis for looking at the impact of TL interference under circumstances where the outcome cannot be ascribed to the existence of a whole-word representation. A further experiment was therefore set up to examine this.

## EXPERIMENT 3: INAPPROPRIATELY PREFIXED ITEMS

Experiment 3 used the same stems as in the first two experiments, but this time, the added prefix did not create a real word (e.g., *reobey*). If the Initial TL condition (e.g., *reboey*) were again to show as much interference as the Medial TL condition (e.g., *reoeby*) relative to the RL Control (e.g., *retuay*), it would strongly indicate that prefixes are stripped off. The whole TL item is not similar to a real word; only its stem is. If disruption of the initial letter of the stem has the same impact on activation of the representation of that stem as has disruption of the medial letters, it would imply that all letters have equal status in activating lexical information, and that the TL Position effect actually arises from a perceptual stage of processing that precedes decomposition. Moreover, the mere existence of TL interference for inappropriately prefixed nonwords would support blind decomposition, because that would be the only way that the stem could be accessed on the basis of inexact letter-position assignment.

### Method

#### *Materials and procedure*

The prefixes of the 42 items used in Experiment 2 were replaced in Experiment 3 with prefixes that no longer created a real word (e.g., *reobey*, *inworthy*, *pretrust*, *unsense*). The same three conditions were used as in Experiments 1 and 2, but this time with the inappropriate prefix: Medial TL (e.g., *reoeby*, *inwrothy*, *preturst*, *unsnese*), Initial TL (e.g., *reboey, inowrthy*, *prertust*, *unesnse*), and RL Control (e.g., *retuay, inarfthy, prelfust*, *unomrse*). The mean length of the prefix was 2.52 letters ($SD = 0.92$). The prefixes used with each stem can again be found in the Appendix along with the stimulus characteristics for each condition.

The real-word distractors of Experiment 2 were also used in Experiment 3, as was the design and procedure of that experiment.

### *Participants*

Experiment 3 recruited a new set of 30 participants from the same pool as the other experiments, with 10 participants per sublist.

## Results and discussion

The 2,000 ms exclusion criterion was exceeded on nine occasions, and the replacement cut-off was applied on 5% of responses. On the basis of making over 50% errors in at least one condition, two participants and one item were removed from the analyses of RTs (but not the analyses of errors). Table 3 presents the mean RT and ER.

The pattern of results was the same as for Experiment 2. The Initial and Medial TL conditions did not differ in either speed or accuracy, all *F*'s $< 1$, while each was significantly slower than the RL Control condition: The interference on the RT measure was $F_1(1,25) = 51.08$, $MSE = 1{,}132.41$, $p < .001$; $F_2(1,38) = 23.83$, $MSE = 2{,}632.69$, $p < .001$ for the Initial TL condition, and $F_1(1,25) = 25.85$, $MSE = 2{,}004.23$, $p < .001$; $F_2(1,38) = 10.06$, $MSE = 4{,}056.43$, $p < .01$ for the Medial TL condition, while the interference on the ER measure was $F_1(1,27) = 9.21$, $MSE = 96.74$, $p < .01$; $F_2(1,39) = 22.03$, $MSE = 53.32$, $p < .001$ for the Initial TL condition, and $F_1(1,27) = 19.21$, $MSE = 75.19$, $p < .001$; $F_2(1,39) = 18.53$, $MSE = 97.34$, $p < .001$ for the Medial TL condition.

It is apparent that the interference observed when the initial letter of a word is disrupted through transposition is increased by the presence of a prefix regardless of whether or not the addition of that prefix creates a real word. Not only did the very weak interference effect for initial letter transpositions in Experiment 1 become highly significant when a prefix was added in Experiments 2 and 3, but there was no differential impact of initial and medial transpositions of the stem in either of the latter two experiments. In order to test these two conclusions explicitly, analyses were carried out across experiments in order to provide a direct comparison of the pattern

TABLE 3

Mean lexical decision times (RT in ms) and % error rates (ER) based on the participant analysis for the inappropriately prefixed items of Experiment 3. The transposed-letter (TL) Position effect is the difference between the Medial and Initial TL conditions. Initial and Medial interference is measured relative to the replaced-letter (RL) Control

| *Condition* | *Example* | *RT* | *ER* |
|---|---|---|---|
| Medial TL | *reoeby* | 733 | 12.72 |
| Initial TL | *reboey* | 737 | 10.62 |
| RL Control | *retuay* | 672 | 2.91 |
| TL Position effect | | −4 | +2.10 |
| Initial interference | | +65 | +7.71 |
| Medial interference | | +61 | +9.82 |

of results for the unprefixed items of Experiment 1 with those for the prefixed items of Experiments 2 and 3, and the latter two experiments were also directly compared.

The comparison of unprefixed and prefixed items revealed that the TL Position effect (i.e., Initial vs. Medial TL conditions) was indeed weaker on response times when the transposition in the initial position of the stem was preceded by a prefix, $F_1(1,82) = 7.17$, $MSE = 1{,}496.87$, $p < .01$; $F_2(1,100) = 4.75$, $MSE = 4{,}486.62$, $p < .05$. The same interaction did not show up clearly on the error measure, however, with only a trend in the participant analysis, $F_1(1,93) = 2.89$, $MSE = 89.23$, $p < .1$, and $F_2(1,117) = 1.58$, $MSE = 185.58$, $p > .1$. The weakness of the interaction for ER came about because the absolute difference between the Initial and Medial TL conditions in Experiment 1 (7.34%) was not sufficiently greater than that for Experiments 2 and 3 (mean of 2.76%) for it to reach significance despite the fact that the former represented more than double the number of errors made in the Initial TL condition while the latter constituted an insignificant proportion of the total errors made. Nevertheless, such an outcome on the accuracy measure does not diminish the fact that the speed measure clearly demonstrated that the addition of a prefix eliminates the TL Position effect.

In addition, both the RT and ER measures revealed a greater interference effect for the Initial TL condition (relative to the RL Control) when there was a prefix than when there was not, $F_1(1,82) = 20.66$, $MSE = 1{,}644.94$, $p < .001$; $F_2(1,100) = 12.49$, $MSE = 2{,}703.28$, $p < .001$ for RT, and $F_1(1,93) = 37.32$, $MSE = 61.19$, $p < .001$; $F_2(1,117) = 15.84$, $MSE = 168.41$, $p < .001$ for ER. In contrast, the same interaction for the Medial TL condition (relative to the RL Control) was only clear for the accuracy measure, with the item analysis of response time being far from significant, $F_1(1,82) = 3.28$, $MSE = 1{,}987.97$, $p < .1$; $F_2(1,100) = 0.37$, $MSE = 3{,}841.25$, $p > .1$ for RT, and $F_1(1,93) = 13.09$, $MSE = 76.92$, $p < .001$; $F_2(1,117) = 7.72$, $MSE = 154.45$, $p < .01$ for ER. Altogether, the comparison of unprefixed and prefixed items strongly indicates that the importance of the initial letter over an internal letter is only evident when the initial letter is physically the first letter of the stimulus.

In relation to the direct comparison of Experiments 2 and 3, the lack of a TL Position effect (Initial vs. Medial) was maintained whether the base formed a real prefixed word or not, $F$'s $< 1$. However, in terms of accuracy, the magnitude of the interference effect (i.e., compared to the RL Control baseline) was greater for both the Initial and Medial TL conditions when the prefix appropriately combined with the stem to form a word (Experiment 2) than when it did not (Experiment 3): The interaction on ER was $F_1(1,54) = 23.68$, $MSE = 83.52$, $p < .001$; $F_2(1,54) = 4.96$, $MSE = 0.05$, $p < .05$ for Initial interference, and $F_1(1,54) = 22.71$, $MSE = 101.85$, $p < .001$; $F_2(1,54) = 4.17$, $MSE = 0.04$, $p < .05$ for Medial interference, and on RT it was $F_1(1,43) = 1.01$, $MSE = 2{,}076.89$, $p > .1$; $F_2(1,63) = 1.83$, $MSE = 3{,}270.79$, $p > .1$ for Initial interference, and $F_1(1,43) = 2.44$, $MSE = 2{,}458.97$, $p > .1$; $F_2(1,63) = 2.36$, $MSE = 4{,}563.36$, $p > .1$ for Medial interference.

It is apparent from these analyses that the TL Position effect was unaffected by whether the base-stem combined appropriately with the prefix or not. In addition, TL interference was greater when the combination was a word (e.g., *disobey*), than when it was not (e.g., *reobey*), regardless of the position of transposition. What is most informative about morphological processing, however, is the fact that the inappropriately prefixed items still showed strong interference relative to the RL Control. Such a finding indicates that prefixes are stripped off and the remaining letters activate a word despite the transposed letters, and that the interference arising from this is exacerbated if it is then established that the prefix can meaningfully recombine with the activated word. One way in which this might occur is depicted in Figure 1 (e.g., Taft, 2003, 2004, 2006; Taft & Ardasinski, 2006; Taft & Nguyen-Hoan, 2010).

As illustrated in the figure, morphemes (bound and free, e.g., *dis* and *obey* respectively) and polymorphemic words (e.g., *disobey*) are both represented at the "lemma" level which mediates between form (orthography in this case) and function (i.e., semantic and syntactic features). The lemma for the polymorphemic word is activated through the lemmas for its constituent morphemes. There is no form representation for the whole polymorphemic word and, as such, decomposition is obligatory. The prefix is stripped off in the sense that it activates its own representation (*dis*) and the remaining letters attempt to activate a unit representing an existing stem. In the case of *disboey* (illustrated) and *disoeby*, there is sufficient overlap for the representation of the stem (*obey*) to be activated. The same procedure holds for *reboey* and *reoeby*, but unlike the case where the prefix is *dis*, it does not generate full activation of any polymorphemic lemma. Therefore, both the appropriately prefixed and inappropriately prefixed TL items will activate lexical information, creating difficulty in making a nonword classification. However, the former will activate more information than the latter, creating greater difficulty.

Note that the alternative dual-route model of orthographic processing proposed by Grainger and Ziegler (2011) cannot explain the data of Experiment 3. Morphological decomposition is restricted to the fine-grained pathway of their model, whereas TL effects only arise within the course-grained pathway. Fine-grained orthographic analysis of *reboey* will fail to access anything after decomposition because *boey* has no orthographic representation, while coarse-grained analysis of *reboey* will fail to

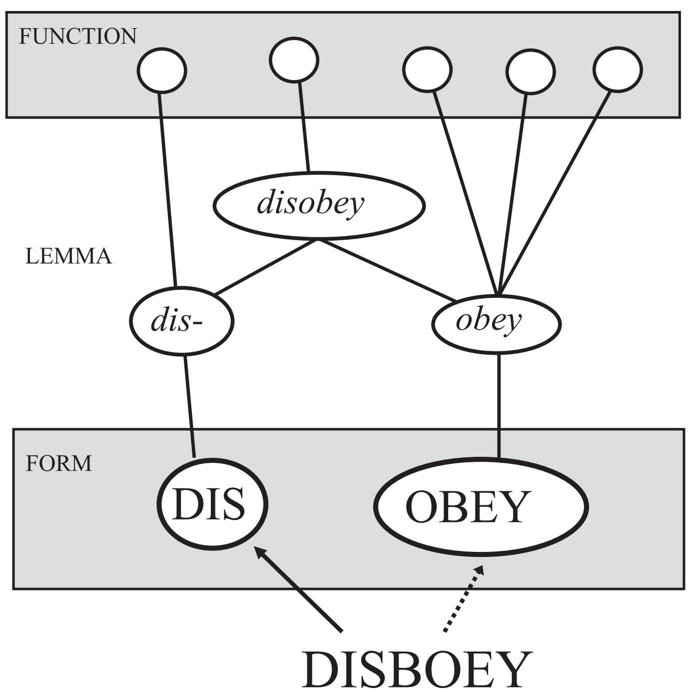


**Figure 1.** Model of the representation of the prefixed word *disobey*. Lemmas represent a level that mediates between form (orthography here) and function (i.e., meaning and syntax) and consists of a morpheme layer and a polymorphemic layer. The lemma for *disobey* is activated through the lemmas for *dis*- and for *obey*. The stimulus is the Initial TL item *disobey*, and the dotted line indicates partial activation arising from an inexact letter match.

activate a whole-word orthographic representation because no such representation exists for *reobey*. As a result, no TL interference should have been observed in Experiment 3, yet it was. An account is therefore required in which the affix is stripped away in order that an attempt be made to activate the stem, with approximate access occurring when letters within the stem are transposed.

Figure 1 depicts an obligatory decomposition model that captures such a procedure. However, the research presented here could also be explained if direct access were possible to the whole word in addition to morphological decomposition. Such a dual-pathways account has been proposed in a number of guises (e.g., Baayen et al., 1997; Bertram et al., 2000; Diependaele, Sandra, & Grainger, 2009). For example, the decompositional component of the model proposed by Diependaele et al. (2009) is similar to Figure 1 (with the morpheme lemmas being referred as "morpho-semantic" units), but there is also parallel activation of a whole-word representation at the form level. Such a model could readily explain TL effects for inappropriately prefixed nonwords (e.g., *reboey*) in terms of the stem being activated via the blind decompositional pathway. In addition, the stronger TL effects observed when the base-word is a prefixed word (e.g., *disboey*) would follow from the fact that the effect could arise from both the decompositional and whole-word pathways.

Whether there is a whole-word pathway or not in addition to decomposition cannot be determined from the present data (but see arguments against it by Taft, 2004, and Taft & Ardasinski, 2006). What the results of Experiment 3 clearly show is that decomposition does occur and, further, that it is automatic, and hence obligatory (e.g., Longtin et al., 2003; Rastle & Davis, 2008; Taft, 2004; Taft & Forster, 1975). If *reboey*, for example, were not decomposed, the confusability of the TL version of its stem with a real word would be avoided because it would be unable to approximately activate any lexical representation. The fact that such interference is nevertheless observed implies that decomposition simply cannot be circumvented.

## EXPERIMENT 4: ITEMS WITH NONPREFIXES

By showing that TL interference occurs even when the prefix does not create a real word when added to the stem, Experiment 3 provides clear evidence for prefix stripping and the accessibility of prefixed words through their stem. Other than the Grainger and Ziegler (2011) account, models of letter position (e.g., Davis, 2010; Gómez et al., 2008; Grainger & van Heuven, 2003; Lee & Taft, 2009, 2011; Whitney, 2001) have little, if anything, to say about morphological processing. The spatial coding model of Davis (2010) comes closest to incorporating morphological processing because the pattern of spatial coding for a word is maintained even when there are other letters preceding that word. That is, the relative pattern of letter coding for *boey* will be the same whether or not it is preceded by a prefix (e.g., *dis* or *re*), and that pattern will be similar to the one that activates the word *obey*. The TL Position effect will nevertheless arise in the absence of a prefix because the extra boost that the initial letter provides to the word level prevents *boey* from strongly activating *obey*, whereas the initial letter of *disboey* or *reboey* has no additional influence on the processing of *obey*.

What the model of Davis (2010) predicts, however, is that the nature of the letters that precede the stem should have no impact on the activation of that stem. This stands in contrast to the prediction of the decomposition model illustrated in Figure 1. As seen in that figure, the prefix is stripped off by virtue of the fact that it coincides with a unit of representation that corresponds to a prefix. That is, *dis* is treated separately from *boey* in *disboey* because it successfully activates an existing unit, and the same happens for the *re* of *reboey*. On the other hand, if the letters appearing before *boey* do not constitute a prefix (e.g., *raboey*), there should be no prefix stripping and, therefore, no activation of the base-word *obey*. The same should be true when the transposition is internal to the base-word (e.g., *raoeby*). According to Davis (2010), however, the pattern of TL interference should be the same as that observed when the letters preceding the base-word form a real prefix (e.g., *reboey*) because the interference arises solely through the similar spatial coding patterns of the final part of the letter-string (i.e., *boey*) and a real word (*obey*). This is tested in Experiment 4.

Taft, Hambly, and Kinoshita (1986) observed interference to lexical decision responses when a bound stem was inappropriately prefixed to create a nonword (e.g., *injoice*), but not when the stem was preceded by a nonprefix (e.g., *ibjoice*). It was concluded that the stem of a word is isolated only when the initial letters are identifiable as a prefix and therefore stripped off. By the same logic, the TL effect observed in Experiment 3 when the base-word was preceded by an inappropriate prefix (e.g., *reobey*) should disappear when it is preceded by a nonprefix (e.g., *raobey*). Such an outcome would strongly support a prefix stripping model and would oppose an account where stems are activated merely through overlap with lexical information (e.g., Davis, 2010).



## Method

### Materials and procedure

The same 42 stems used in the other experiments were preceded with a set of letters that corresponded to the inappropriate prefix used in Experiment 3, but with one letter changed so that it was no longer a prefix (e.g., *raobey*). The same three experimental conditions were again examined: Medial TL (e.g., *raoeby, itwrothy, dreturst*, *ugsnese*), Initial TL (e.g., *raboey, itowrthy*, *drertust*, *ugesnse*), and RL Control (e.g., *ratuay, itarfthy*, *drelfust*, *ugomrse*). A new set of 42 real-word distractors were selected, none of which began with a prefix and were of similar structure to the nonword items and of similar mean length (e.g., *umbrella*, *amnesty*, *partner*, *liaison*). The design and procedure were otherwise the same as in the other experiments. The set of letters added to each stem can be found in the Appendix along with the stimulus characteristics for each condition.

### Participants

A further group of 30 participants were recruited from the same pool as the other experiments, with 10 participants per sublist.

## Results and discussion

Three responses exceeded the 2,000 ms acceptance criterion, while the replacement cut-off was used for 6% of responses. With the error rate being quite low, it was unnecessary to eliminate any participant or item from the RT analyses. Table 4 reports the mean RT and ER.

No significant differences were found between any of the conditions. For the analyses of RT, all *F*'s were $< 1$, as was also the case for the comparison of the Initial and Medial TL conditions on ER. The trend for TL interference effects on ER failed to reach significance for either the Initial TL condition, $F_1(1,27) = 1.08$, $MSE = 13.21$,

TABLE 4
Mean lexical decision times (RT in ms) and % error rates (ER) based on the participant analysis for the items with nonprefixes of Experiment 4. The transposed-letter (TL) Position effect is the difference between the Medial and Initial TL conditions. Initial and Medial interference is measured relative to the replaced-letter (RL) Control

| *Condition* | *Example* | *RT* | *ER* |
|---|---|---|---|
| Medial TL | *raoeby* | 654 | 3.34 |
| Initial TL | *raboey* | 652 | 2.87 |
| RL Control | *ratuay* | 655 | 1.90 |
| TL Position effect | | +2 | +0.47 |
| Initial interference | | −3 | +0.97 |
| Medial interference | | −1 | +1.44 |

$p$ >.1; $F_2$(1,39) = 1.09, $MSE$ = 23.30, $p$ >.1, or the Medial TL condition, $F_1$(1,27) = 2.07, $MSE$ = 15.15, $p$ >.1; $F_2$(1,39) = 1.81, $MSE$ = 25.22, $p$ > .1.

When directly compared to the inappropriately prefixed items of Experiment 3, the lack of a difference between the Initial and Medial TL conditions was maintained, all $F$'s < 1.5, but the Initial TL items showed greater interference when they had real prefixes, $F_1$(1,53) = 23.69, $MSE$ = 1,431.85, $p$ <.001; $F_2$(1,77) = 17.17, $MSE$ = 1,932.55, $p$ <.001 and $F_1$(1,55) = 6.31, $MSE$ = 54.00, $p$ <.05; $F_2$(1,78) = 11.15, $MSE$ = 38.31, $p$ <.001 for RT and ER, respectively, as did the Medial TL items, $F_1$(1,53) = 19.66, $MSE$ = 1,463.58, $p$ <.001; $F_2$(1,77) = 7.88, $MSE$ = 2,693.53, $p$ <.01 and $F_1$(1,55) = 10.32, $MSE$ = 46.21, $p$ <.01; $F_2$(1,78) = 10.32, $MSE$ = 61.28, $p$ <.01.

It is clear, then, that TL interference is observed only when the letters preceding the stem form a prefix. When they form a nonprefix, any effect of transposed letters disappears. Such a finding implies that the matching of a letter-string to lexical information proceeds from left-to-right (or outside-in) such that an embedded word is not isolated unless the letters preceding it match a morphemic representation and are hence treated as a unit. In relation to the framework depicted in Figure 1, this amounts to saying that the overlap between *boey* and *obey* is not achieved until *dis* is found to match with a unit of representation. One way to conceive of this is if letters are assigned to an onset, vowel, or coda position at the same time that affixes are identified. So, once the letters *d*, *i*, and *s* are found to combine to activate a prefix unit, the remaining letters must be assigned to their subsyllabic position (i.e., onset, vowel, or coda) and this is a relatively imprecise procedure when the letter is laterally masked, hence producing TL interference (cf. Lee & Taft, 2009, 2011). When the initial letters of the stimulus do not form a prefix (e.g., *raboey*), the first letter is readily assigned to an onset or vowel position (depending on whether it is a consonant or not) and an attempt is made to find a matching lexical item that begins with that letter (e.g., *rabbit*).

The results would be hard to explain within the spatial coding model of Davis (2010) as it currently stands because *boey* should overlap with *obey* to the same extent whether it be preceded by *ra* or *re*. While the initial position in the letter-string of the *r* of *ra* will provide a strong boost in activation to words beginning with *r* (in competition with *obey*), the same should be true of the *r* of *re*. It seems that some form of morphological decomposition must be explicitly incorporated into the model, as indeed it must in relation to any of the other models of letter-position assignment.

## EXPERIMENT 5: DIGIT-PREFIXED ITEMS

If a prefixed word is recognised through the activation of its stem after the prefix is stripped, an explanation is needed for the failure to find a TL Position effect under such circumstances (i.e., Experiments 2 and 3) given that the beginning of the unit being activated is disrupted. The most obvious account is that the initial letter of the stem has privileged status in the activation of that stem only when it is perceptually salient, namely, when in the initial position of the letter-string itself (as in Experiment 1). It seems that the blank space appearing before the initial letter provides important information about the position of that letter. So, the *b* of *boey* can be easily discerned as the initial letter of the stimulus and this allows it to play a critical role in activating lexical information, hence avoiding activation of *obey.* There is no basis here for saying whether the critical role of the perceptually salient initial letter arises from its faster activation (e.g., Whitney, 2001; Whitney & Cornelissen, 2005, 2008), its specialised activation (e.g., Davis, 2010), its tighter tuning (Gómez et al., 2008), its identification as an onset (e.g., Lee and Taft, 2009, 2011), or for some other reason. All that can be said is that the advantage of the initial letter disappears when it is preceded by a prefix and this implies that it is a product of low level perceptual processing. The final experiment was carried out to test this conclusion directly.

In order to establish how low a level the source of the TL Position effect is, Experiment 5 took the unprefixed items of Experiment 1 and added a set of digits at the beginning (e.g., *527boey*). The lexical decision task therefore required participants to ignore the digits when responding to the letter-string. If the presence of the digits were to eliminate the TL Position effect, it would strongly indicate that it is the empty space next to the initial letter that provides its advantage in processing.



### Method

#### *Materials and procedure*

The 42 prefixed items of Experiment 2 were used as the basis for the items in Experiment 5. Each prefix was replaced with a row of digits of the same length, and the same prefix was replaced with the same row of digits. The final digit was never a one or a zero (because of their confusability with the letters *l* and *o*, respectively). The three experimental conditions used in the other experiments were again set up (e.g., Medial TL *527oeby*, *78wrothy*, *827turst*, *414snese*; Initial TL *527boey, 78owrthy*, *827rtust*, *414esnse*; and RL Control *527tuay, 78arfthy*, *827lfust*, *414omrse*). The font size of the digits was reduced relative to the letters (18 vs. 20 point) in order that they could be more readily distinguished from each other (most notably making the initial letter *l* distinct from the digit *1*).

The real-word distractors were taken from Experiment 1, each being preceded by a row of digits from the same pool as that used with the nonword items. The design and procedure were the same as in Experiment 1, except that participants were instructed that each item would have a row of numbers in front of it and that they were to ignore this when making their lexical judgement of the letter-string. The digits appended to each item can be found in the Appendix.

#### *Participants*

A new set of 45 participants were recruited from the same pool as the other experiments, with 15 participants per sublist.

## Results and discussion

The 2,000 ms exclusion criterion was breached for 11 responses, while the replacement cut-off was applied to 5% of responses. For the analysis of RTs, one participant and two items were removed from the participant and item analysis respectively owing to ER of greater than 50% in at least one condition. Mean RT and ER are found in Table 5.

Comparison of the Initial and Medial TL conditions revealed no TL Position effect, $F$'s $< 1$ for RT, and $F_1(1,42) = 2.13$, $MSE = 61.45$, $p > .1$; $F_2(1,39) = 1.39$, $MSE = 88.65$, $p > .1$ for ER. In contrast, there was highly significant interference relative to the RL Control condition not only for the Medial TL condition, $F_1(1,41) = 37.16$, $MSE = 991.64$, $p < .001$; $F_2(1,37) = 8.04$, $MSE = 2{,}953.43$, $p < .01$ and $F_1(1,42) = 18.11$, $MSE = 104.25$, $p < .001$; $F_2(1,39) = 21.77$, $MSE = 81.43$, $p < .001$ for RT and ER, respectively, but also for the Initial TL condition, $F_1(1,41) = 33.86$, $MSE = 1{,}056.26$, $p < .001$; $F_2(1,37) = 21.07$, $MSE = 1{,}724.75$, $p < .001$ and $F_1(1,42) = 19.80$, $MSE = 51.73$, $p < .001$; $F_2(1,39) = 19.24$, $MSE = 49.94$, $p < .001$ for RT and ER, respectively.

A direct comparison of Experiment 5 with Experiment 1 showed that TL Position indeed had a stronger impact on RTs when there were no digits, $F_1(1,80) = 9.40$, $MSE = 1{,}287.08$, $p < .01$; $F_2(1,74) = 8.06$, $MSE = 2{,}330.80$, $p < .01$, though the interaction on ER was only significant in the participant analysis, $F_1(1,81) = 4.96$, $MSE = 53.01$, $p < .05$; $F_2(1,77) = 2.75$, $MSE = 132.68$, $p = .1$. The Medial TL condition showed the same amount of interference in the two experiments, with all $F$'s $< 1.2$ for the interaction. The Initial TL condition did show increased interference when preceded by digits, though the item analyses were only strong trends, $F_1(1,80) = 4.63$, $MSE = 1{,}111.07$, $p < .05$; $F_2(1,74) = 3.87$, $MSE = 1{,}730.86$, $p < .1$ and $F_1(1,81) = 5.35$, $MSE = 41.39$, $p < .05$; $F_2(1,77) = 3.71$, $MSE = 56.52$, $p < .1$ for RT and ER, respectively.

The results of Experiment 5 strongly indicate that the TL Position effect arises at a low level of perceptual processing, presumably with lateral masking coming into play. It does not seem to matter whether the material that comes before the initial letter is also composed of letters (i.e., a prefix) or whether it belongs to a different category altogether (i.e., digits). Both lead to activation of the base-word even when the initial letter is disrupted through transposition.[3] Such a result clearly shows that the original

TABLE 5

Mean lexical decision times (RT in ms) and % error rates (ER) based on the participant analysis for the digit-prefixed items of Experiment 5. The transposed-letter (TL) Position effect is the difference between the Medial and Initial TL conditions. Initial and Medial interference is measured relative to the replaced-letter (RL) Control

| *Condition* | *Example* | *RT* | *ER* |
|---|---|---|---|
| Medial TL | *527oeby* | 765 | 11.53 |
| Initial TL | *527boey* | 765 | 9.12 |
| RL Control | *527tuay* | 725 | 2.37 |
| TL Position effect | | +0 | +2.41 |
| Initial interference | | +40 | +6.75 |
| Medial interference | | +40 | +9.16 |

[3] It is possible the mere presence of a single hash-mark would also eliminate the TL Position effect (e.g., #*boey* vs. #*oeby*), but this is not explored here because exactly how low a level of processing is involved is not the central issue.

assumption underlying the prediction of a TL Position effect for prefixed words was misguided. It is not so much that the lexical representation for the stem is more sensitive to initial than medial letters, but rather that the perceptual salience of the initial letter has an impact. It is clear that the TL Position effect arises earlier than any consideration of morphological structure.

# GENERAL DISCUSSION

Together, the five experiments reported in this paper tell a clear story relevant to the issues of both morphological decomposition and letter-position processing. By showing that TL interference occurs when a letter-string begins with an existing prefix (Experiments 2 and 3 vs. Experiment 4), it is apparent that this prefix is stripped from the putative stem which, in turn, is fed into the lexical system for identification. When two of the letters within that stem are transposed, approximate activation of lexical information leads to interference in classifying the letter-string as a nonword regardless of the position of that transposition within the stem. The results support a model of lexical processing where early morphological decomposition occurs (with or without parallel whole-word access) and lexical access of the stem is based on an input representation for which letter position is inexactly encoded. It is additionally argued that Experiment 3 shows that such decomposition is obligatory, since it would have been more efficient to have avoided it if that were possible.

It was initially thought that transposition of the initial letter of the stem might be reduced if prefix stripping occurred, but this was shown to be wrong. The TL interference observed in Experiment 3 when the base-word was an inappropriately prefixed stem can only be explained in terms of prefix stripping, yet there was no TL Position effect. The reduction in interference when the transposition was in initial position was only observed when the first letter was perceptually salient as a result of the space before it (Experiment 1 vs. 5).

The combined examination of inexact encoding (i.e., the TL effect) and morphological processing speaks to the way in which models that address the former will need to consider the involvement of the latter. Most models that seek to explain TL effects have little if anything to say about morphological processing.



## Spatial coding and morphology

There is the potential for morphological decomposition within the spatial coding model of Davis (2010) in as much as the pattern of activation for a letter-string will be found within the activation pattern of any affixed version of that letter-string, whether it be a word or nonword. However, the same will also be true when a nonexisting affix is attached, which means that TL effects should be the same regardless of whether the base-item is a prefixed nonword (e.g., *reboey*) or a nonprefixed nonword (e.g., *raboey*). Yet the TL interference observed in Experiment 3 with inappropriately prefixed nonwords did not arise in Experiment 4 when the appended letters did not form a real prefix. This means that morphological factors were specifically involved, rather than mere orthographic overlap with an existing word as suggested by Davis (2010).

## Open bigrams and morphology

In models that incorporate representations that mediate between letters and words in the form of open bigrams (e.g., Grainger & van Heuven, 2003; Grainger &

Ziegler, 2011; Whitney, 2001; Whitney & Cornelissen, 2005, 2008), an account needs to be given of the relationship between the analysis of the letter-string into such bigrams and the analysis of the letter-string into morphemes. Grainger and Ziegler (2011) directly address this issue, but their solution of having bigram and morphological analysis in separate pathways is contradicted by the results of Experiment 3. If TL effects were to only arise within a pathway where open bigrams activate whole-words, an affixed nonword with a transposed stem (e.g., *reboey*) would never be able to activate the correct form of the stem (*obey*) to produce interference (or produce priming in the case of *wranish-WARN*; Beyersmann et al., 2011).

If, however, morphological decomposition preceded the activation of open bigrams within the same pathway, it would mean that TL effects arise after decomposition and that an affix would therefore fail to be identified if its letters were transposed. Thus, the nonword *attachmnet* would show no interference from the existence of the word *attachment* (relative to *attachmrat*) because the activation of the affix *ment* from *mnet* requires the involvement of open bigrams (i.e., *mn*, *me*, *mt*, *nt*, and *et*) which have not yet come into play. Similarly, *msijudge* would show no interference from the existence of *misjudge* (relative to *mfojudge*). Since such an outcome is highly unlikely (though admittedly, untested), it is apparent that morphological decomposition must follow any bigram analysis. If so, however, it is hard to see how there could be interference in Experiment 3 (e.g., for *reboey*) and not for Experiment 4 (e.g., for *raboey*). Any interference would have to arise from the subset of bigrams that overlaps between the stimulus and the stem (e.g., the *oe*, *be*, *by*, *oy*, and *ey* of *reboey* and *obey*), but these would be exactly the same whether the stimulus begins with a prefix (e.g., *re*) or a nonprefix (e.g., *ra*). It would therefore seem necessary to say that decomposition and bigram activation occur concurrently, such that affixed words are activated through separate representations of their stem and affix and that both are mediated through open bigram representations. So, the prefix *mis* is responsive to *mi*, *ms*, and *is*, and hence is sufficiently activated by *msi* for that letter-string to be treated separately as a prefix.

## Imprecise letter position assignment and morphology

For similar reasons, models that explain TL effects through the imprecise insertion of letters either into positional slots (e.g., Gómez et al., 2008; Norris et al., 2010) or into subsyllabically defined slots (e.g., Lee & Taft, 2009, 2011) would also have to say that decomposition and approximate letter assignment co-occur. For *boey* to activate *obey* when preceded by an inappropriate prefix (e.g., *reboey*) and not when preceded by a nonprefix (e.g., *raboey*), approximate access of the stem needs to follow, or be concurrent with, decomposition. However, identification of the affix for the purposes of decomposition would seem to also require approximate access, since it is likely that a transposed affix will be stripped to reveal the stem (such as in *attachmnet* and *msijudge*), and therefore approximate access and decomposition are concurrent processes. This is captured in Figure 1 where decomposition is determined by the success of activating units corresponding to the component morphemes. When a letter is out of position, it will nevertheless allow partial activation of a lemma unit and therefore TL interference will ensue. This will be true whether or not the transposition occurs within the stem or the affix, or indeed straddles the two.

## Conclusions

Despite finding that the initial letter of the stem behaves like a word-internal letter rather than a word-initial letter, the results of this study indicate that a prefixed letter-string is automatically decomposed. Obligatory decomposition is implied by the finding that the stem of a prefixed nonword (e.g., *obey* in *reobey*) is activated even when two of its letters are transposed. In such a case, there would be no interference to nonword classification times if the letter-string could be treated as a whole. The reason why disruption of the stem-initial letter produces as much interference as disruption to stem-internal letters is that the initial letter of a word is only more helpful than other letters in its contribution to word recognition as a result of its perceptual salience. It is shown that the advantage of the initial letter disappears when the space to its left is filled with other characters, even characters that are not part of the letter-string to be processed (i.e., digits). It is apparent that a complete model of orthographic processing must not only provide an account of imprecise coding of letter position that is reduced when the letter and/or its position is perceptually salient, but must integrate this account with the idea that affixes are treated separately from their stems during the processing of affixed words.

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# APPENDIX

The following are the Medial TL, Initial TL, and RL Control items for Experiment 1. In parentheses are the prefix, inappropriate prefix, non-prefix, and digit string that were attached to the item in Experiments 2, 3, 4, and 5, respectively.

oeby, boey, tuay (dis, re, ra, 527); lcuky, ulcky, arnky (un, in, an, 78); pirnt, rpint, hcint (re, un, ub, 94); palced, lpaced, rfaced (mis, de, da, 827); vlaued, avlued, ajrued (de, in, id, 38); euqal, qeual, boeal (un, dis, dos, 78); snaity, asnity, osmity (in, inter, ipto, 32); calim, lcaim, rpaim (pro, in, ib, 645); borken, rboken, rpaken (un, in, if, 78); gianed, agined, omuned (re, un, ul, 94); rpeute, erpute, olnute (dis, un, um, 527); bleief, eblief, aprief (dis, im, om, 527); vlaid, avlid, otlid (in, trans, treps, 32); mtaure, amture, umgure (pre, dis, lis, 194); cretain, ecrtain, ipltain (un, ad, ed, 78); fersh, rfesh, lcish (re, in, ip, 94); argee, garee, dilee (dis, non, nin, 527); tihnk, htink, lgink (re, de, du, 94); ogranic, roganic, sulanic (in, re, we, 32); derss, rdess, ltuss (un, mis, mic, 78); oepned, poened, sianed (re, de, fe, 94); jguded, ujdged, ockged (mis, re, me, 827); lkie, ilke, arbe (dis, inter, oster, 527); wrothy, owrthy, arfthy (un, in, it, 78); mvoes, omves, anbes (re, dis, tis, 94); qiuet, uqiet, ebuet (dis, mis, mas, 527); konwn, nkown, stawn (un, de, le, 78); porve, rpove, lbive (dis, un, us, 527); cerate, rceate, hwiate (re, un, us, 94); driect, idrect, iblect (in, per, pem, 32); hpapy, ahppy, ortty (un, inter, isker, 78); hmuane, uhmane, ihlane (in, ad, od, 32); oepned, poened, rauned (un, mis, vis, 78); celan, lcean, rpoan (un, re, ra, 78); slouble, osluble, esmuble (in, re, ra, 32); turst, rtust, lfust (mis, pre, dre, 827); lnog, olng, erng (pro, mis, jis, 645); brith, ibrth, aprth (re, im, am, 94); snese, esnse, omrse (non, un, ug, 414); lyoal, olyal, elnal (dis, in, iv, 527); sopken, psoken, ldoken (un, re, me, 78); biult, ubilt, epult (re, en, an, 94)

The table below reports mean neighbourhood size (*N*), number of words with one more or one less letter (sub and super-sets), and token and type bigram frequency (BF) for the three conditions in each experiment. Values are taken from N-Watch (Davis, 2005).

| | *N* | | | *Sub and super-sets* | | | *Token & Type BF* | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Medial TL* | *Initial TL* | *RL Control* | *Medial TL* | *Initial TL* | *RL Control* | *Medial TL* | *Initial TL* | *RL Control* |
| Expts. 1 & 5 | 0.19 | 0.14 | 0.21 | 10 | 9 | 8 | 800.30 | 870.56 | 797.55 |
| | | | | | | | 49.06 | 44.10 | 44.11 |
| Expt. 2 | 0 | 0 | 0 | 1 | 2 | 1 | 525.01 | 564.15 | 602.01 |
| | | | | | | | 61.60 | 65.72 | 66.50 |
| Expt. 3 | 0 | 0 | 0.03 | 0 | 0 | 1 | 518.77 | 560.28 | 559.18 |
| | | | | | | | 60.25 | 65.83 | 65.07 |
| Expt. 4 | 0 | 0 | 0 | 0 | 0 | 0 | 371.47 | 441.18 | 447.13 |
| | | | | | | | 45.42 | 52.64 | 52.34 |