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Do Morphemes Matter when Reading Compound Words with Transposed Letters? Evidence from Eye-Tracking and Event-Related Potentials

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Abstract

The current study investigates the online processing consequences of encountering compound words with transposed letters (TLs), to determine if TLs that cross morpheme boundaries are more disruptive to reading than those within a single morpheme, as would be predicted by accounts of obligatory morpho-orthopgrahic decomposition. Two measures of online processing, eye movements and event-related potentials (ERPs), were collected in separate experiments. Participants read sentences containing correctly spelled compound words (*cupcake*), or compounds with TLs occurring either across morpheme boundaries (*cucpake*) or within one morpheme (*cupacke*). Results showed that between- and within-morpheme transpositions produced equal processing costs in both measures, in the form of longer reading times (Experiment 1) and a late posterior positivity (Experiment 2) that did not differ between conditions. Findings converge to suggest that within- and between-morpheme TLs are equally disruptive to recognition, providing evidence against obligatory morpho-orthographic processing and in favor of whole-word access of English compound words during sentence reading.

Keywords

eye movements; ERPs; compound words; morphological processing; LPC/P600

Introduction

Years of accumulated work have focused on the question of how readers use morphemes to recognize words. Much work from the behavioral literature suggests that readers recognize multimorphemic words at least partially through the recognition of their constituent morphemes. The majority of this evidence comes from research using masked priming in

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conjunction with the lexical decision task (see review in Diependaele, Grainger, & Sandra, 2012), which only provides information about the end-state of processing, specifically, how long it takes a reader to respond to a word following a particular prime condition. In the current investigation, we will instead ask whether evidence of morphological decomposition can be seen during online processing measured in the course of sentence reading, in order to understand whether readers engage in similar processes while reading words silently for comprehension. In order to test for effects of morphological decomposition, we employ the transposed letter (TL) manipulation using English compound words. Our main experimental question asks whether letter transpositions that cross a morpheme boundary cause more disruption to reading than those that occur within a single morpheme. In order to study online processing, we will collect two different measures in two experiments: 1) eye-tracking during natural reading, and 2) event-related brain potentials (ERPs) elicited during word-by-word sentence reading. This study is the first to report both eye movement and ERP effects elicited by cross-morpheme letter transpositions in English compound words. Our unique use of these two complimentary measures allows us to present a more complete picture of how letter transpositions impact the recognition of compounds during sentence reading.

Morphological Decomposition

An extensive body of work in the behavioral domain has produced strong evidence that individual morphemes become active when single multimorphemic words are viewed in isolation (for reviews, see Amenta & Crepaldi, 2013; Diependaele, Grainger, & Sandra, 2012). However, the exact nature of this activation, and how it is used to facilitate typical word recognition, are both still open questions. Some work suggests that words are decomposed into their morphemes very early in the recognition process based on their orthography, a process known as morpho-orthographic processing (Rastle & Davis, 2008). For example, Rastle, Davis, and New (2004) found facilitation for lexical decision times from morphologically transparent primes (*cleaner-CLEAN*), as well as monomorphemic pseudo-morphological primes (*corner-CORN*) ending with the same letter string. In contrast, they did not find priming from non-morphological primes, which ended in a letter string that was *not* a suffix in the English language (*brothel-BROTH*), even though these primes and targets shared the same number of overlapping letters as the other prime-target pairs. Many follow-up studies have found similar results (for a review, see Rastle & Davis, 2008), which have collectively been taken as evidence for morpho-orthographic processing, in which words are automatically decomposed into stems and affixes based on their apparently orthographically-based morpheme structure, regardless of whether that is reflective of true underlying morphology. This “affix stripping” process allows the stem to facilitate target processing.

Recently, it has been proposed that readers may recognize morphologically complex words through a second “whole-word” route that allows complex words to activate their whole-word representation *without* being mediated by morpheme recognition (Diependaele, Sandra, & Grainger, 2009). This whole-word recognition route, which is thought to operate in parallel with the morpho-orthographic route, proposes that activation spreads from the whole-word representation to a more abstract “morpho-semantic” level that codes for relationships between lexical units (i.e., between a word and its constituent morphemes). This level, in turn, sends top-down activation to that word's morphemes, thus facilitating stem processing. Some evidence in favor of a whole-word route to complex word recognition comes from the finding that transparent words have been found to produce a bigger priming benefit than do opaque words in a masked-priming lexical decision paradigm (e.g., Diependaele, Sandra, & Grainger, 2005, 2009; Feldman, O'Connor, & Moscoso del Prado Martin, 2009; Morris, Frank, Grainger, & Holcomb, 2007). However, this effect is inconsistent, as other studies have observed equal priming for transparent and opaque primes (e.g., Beyersmann, Coltheart, & Castles, 2012; Beyersmann et al., 2016; Marelli, Amenta, Morone, & Crepaldi, 2013; see review in Rastle & Davis, 2008). Other evidence in favor of a whole-word route comes from the finding that equally large stem priming effects are observed from primes containing both real and fake affixes combined with real stems (Beyersmann, Cavali, Casalis, & Colé, 2016; Diependaele, Morris, Serota, Bertrand, & Grainger, 2013; Morris, Porter, Grainger, & Holcomb, 2011). In contrast to this, obligatory decomposition theories would propose that fake-affixed words should not prime the stem because the fake affix cannot be stripped away. Again, however, these findings are inconsistent: fake affixes sometimes produce reduced priming relative to real ones (Longtin & Meunier, 2005), as would be predicted by obligatory decomposition theories, and Beyersmann and colleagues (Beyersmann, Casalis, et al., 2015; Beyersmann, Cavalli, et al., 2016) has shown that an individuals' reading proficiency may play an important role in how effectively stems can be used to access the whole-word listing.

In light of these inconsistent findings, the question of whether morpho-orthographic processing is *obligatory* for the recognition of morphologically complex words or whether whole-word units are available in parallel with these morphological subunits remains the topic of much debate. Recent work (Beyersmann, Ziegler, et al., 2016) suggests that obligatory morpho-orthographic processing may be restricted to the masked priming paradigm, and may not be present in tasks that involve semantics (Marelli, et al., 2013) or that are even more form-based (Duñabeita, Kinoshita, & Norris, 2011). Even less clear is the role of context in shaping the processing that unfolds during word recognition. The masked-priming lexical decision paradigm, which has formed the basis for much of the empirical work and resultant theorizing in this area (c.f., Amenta et al., 2015; Marelli et al., 2013; Marelli & Luzzatti, 2012), differs from natural reading in several important ways. Masked-priming tasks are designed to examine implicit influences from primes, whereas in normal reading the context is processed overtly. Moreover, lexical decisions can be made on the basis of a more shallow analysis of word properties than the semantic processing involved in comprehending a word's meaning. The current experiment moves away from the use of the lexical decision task and from masked-priming more generally to ask whether readers engage in obligatory morphological decomposition of English compound words during sentence reading. To do so, we will employ a transposed-letter paradigm, which we will review next.

Transposed Letter (TL) Similarity Effects from Masked Priming

The transposed letter similarity effect provides a tool that can further elucidate the circumstances under which morphological decomposition takes place. In a standard TL paradigm, primes contain letter pairs that have either been transposed or contain visually similar replacement letters (RL). Findings generally show that TL primes produce faster response times than RL primes in lexical decision tasks (e.g., Perea & Lupker, 2003). This is true even of non-adjacent transposed letters with one intervening letter (Perea & Lupker, 2004), two intervening letters (Perea, Duñabeitia, & Carrieras, 2009) or primes containing multiple pairs of transpositions (Guerrera & Forster, 2008). The reasoning behind the application of this paradigm to questions of morphological decomposition is as follows: if readers obligatorily decompose words into their constituent morphemes in order to be recognized, then letter transpositions that cross morpheme boundaries should be more disruptive to this process, thus providing *less* target facilitation than letter transpositions that stay within a single morpheme. Conversely, equal priming from transpositions that occur within and across morpheme boundaries is sometimes taken as evidence *against* the idea of obligatory morpho-orthographic processing (but cf. Taft & Nillsen, 2013), because disrupting the morpheme boundary does not slow recognition. This is not to say that the constituent morphemes are not eventually activated, either through the whole-word morpho-semantic route (Dipendaele et al., 2009) or because the assignment of letters to morphemes might be underspecified in the early stages of processing (McCormick, Rastle, & Davis, 2008, 2009), allowing even TLs to activate the correct morphemes. However, the question of whether between- and within-morpheme letter transpositions differ from each other in the amount of priming they produce provides a good starting point for asking about the presence of early, obligatory morphological decomposition outside of the specific task demands imposed by lexical decisions.

A large number of studies have thus used the TL paradigm to look at obligatory morphological decomposition, with inconsistent results across the literature. Some work finds evidence in favor of morphological decomposition. For example, Christianson, Johnson, and Rayner (2005) showed that naming latencies were faster for English compound words following primes that were either identical to the target (*sunshine*) or contained a within-morpheme TL (*sun**hs**ine*), relative to primes containing a between-morpheme TL (*su**sn**hine*) or a single replacement letter (*suns**b**ine*) (although the critical within-morpheme vs. between-morpheme comparison was only significant by subjects and not items). They also found that cross-morpheme letter transpositions failed to prime derived words (i.e., boas**et**r—boaster), although monomorphemic words *did* benefit from a TL in the same location (blus**et**r—bluster). Duñabeitia, Perea and Carreiras (2007) replicated the results for affixed words in Basque and Spanish, finding TL priming for monomorphemic words, but not for cross-morpheme TLs in affixed words. Furthermore, in a large-scale study, Duñabeitia, Perea, and Carreiras (2014) again found greater priming for within- relative to between-morpheme letter transpositions. This result was, however, limited to a subset of participants that were identified as "fast" responders in a post-hoc analysis of their lexical decision times. Together, the lack of TL priming across morpheme boundaries observed in these studies suggests that disrupting the readers' ability to quickly recognize and/or strip away morphemes hinders word recognition.

In contrast, a growing body of research has found equally large TL priming effects from transpositions that occur within and across morpheme boundaries in affixed words. For example, Rueckl and Rimzhim (2011) employed a lexical decision task with primes containing the derivational suffix –*er*, and the stems as the targets. The primes could contain transposed or replacement letters on the final letters of the stem (TL: *tea**hc**er-TEACH*, RL: *tea**ks**er-TEACH*), or across the stem-affix boundary (TL: *teac**eh**r-TEACH*, RL: *tea**rdi**r-TEACH*). They found significant facilitation following both within- and across-morpheme TL primes relative to the replacement letter control. Several recent studies have found similar results of equal within- and across-morpheme TL priming in both English (Beyersmann, Coltheart, & Castles, 2012; Beyersmann, McCormick, & Rastle, 2013; Diependaele et al., 2013) and Spanish (Sánchez-Gutiérrez & Rastle, 2013). Finally, Perea and Carrieras (2006) found significant TL versus RL priming across a morpheme boundary in Basque compound words. Together, these studies suggest that priming is *not* reduced when the two transposed letters cross morpheme boundaries, and thus, provide evidence in favor of a whole-word route to complex word recognition, which is not obligatorily mediated by morpho-orthographic decomposition.

TL Effects in Sentence Reading

The evidence reviewed above from the masked priming literature regarding morphological decomposition proved to be inconsistent with respect to whether cross-morpheme letter transpositions are more disruptive than within-morpheme TLs, although most recent evidence seems to suggest no difference in priming elicited by these two prime types. One drawback is that these studies all examined the processing of single words in isolation (preceded only by a brief masked prime), providing no information about whether morphological decomposition takes place under more natural reading conditions. One set of studies has tried to bridge this divide by combining masked priming with self-paced reading. In this paradigm, readers receive brief (50ms) masked primes before viewing targets in a word-by-word sentence reading paradigm. In the first study to utilize this paradigm (called SPaM), Luke and Christianson (2012) found that TL priming can be achieved in this fashion (relative to replacement letters), and further, that this benefit was eliminated for highly predicw targets. This corroborates findings from the ERP literature that readers predict even the orthography of expected words in highly constraining sentences (Laszlo & Federmeier, 2009), and, therefore, that a TL prime that violates this orthographic prediction does not facilitate reading times. Other work from Luke and Christianson (2013, 2015) using this paradigm has found reduced or absent cross-morpheme TL priming in inflected English past-tense verbs, an effect that is modulated by both the frequency profile of the inflected words (Luke & Christianson, 2013) as well as the predictability of the inflectional morpheme (Luke & Christianson, 2015). Thus, these two studies provide evidence in favor of morphological decomposition during reading in a sentence context, at least within inflected words under certain circumstances.

Other work has combined TL priming with the boundary change paradigm, which takes advantage of the fact that readers extract letter identity information from the next word in the sentence when it is visible in the parafovea (for review, see Schotter, Angele, & Rayner, 2012). Parafoveal information can be thought of as an analogue to a masked prime, in that it is received just before readers fixate the target itself, and it has less visual acuity relative to foveal processing. The preview readers receive of the upcoming word is manipulated, and the critical outcome measure is the preview benefit, or the facilitation for reading times on the target following a valid versus invalid preview. Using this paradigm, Johnson and colleagues have replicated the classic TL priming effect, showing a bigger preview benefit following TL versus RL previews (Johnson, Perea, & Rayner, 2007; Johnson & Dunne, 2012). Other work has also investigated TL effects using the boundary-change paradigm to assess the importance of word-initial letters (Pagán, Blythe, & Liversedge, 2015) for both child and adult readers (Tiffin-Richards & Schroder, 2015). To our knowledge, the only study that has examined the effects of cross-morpheme letter transpositions during sentence reading using the boundary change paradigm -- Masserang and Pollatsek (2012) -- found equally large preview benefits following TLs that did and did not cross a prefix boundary, relative to RLs in the same location -- providing evidence *against* the obligatory morphoo-orthographic processing of affixed words during sentence reading.

Finally, some work has simply presented readers with transposed letter nonwords under full viewing conditions to better understand the processing costs elicited by overt misspellings—as will be done in the current study. Unsurprisingly, Rayner, White, Johnson, and Liversedge (2006) found global reading time costs in sentences containing TL nonwords, including longer sentence reading times, longer average fixation durations, and an overall larger number of fixations and regressive saccades. In a follow-up study, White, Johnson, Liversedge, and Rayner (2008) found that word-external transpositions (i.e., involving the word's first two letters, or last two letters) elicited longer reading times than word-internal transpositions, with the most disruption caused by word-initial transpositions (see also Johnson & Eisler, 2012, and Luke & Christianson, 2012, for more evidence as to the importance of word-external letters). One caveat to these two sets of findings is that *every* word of the sentence over a certain length received the letter transposition manipulation, which may have altered global reading strategies. It has also been shown that non-adjacent letter transpositions produce greater reading time costs than adjacent letter transpositions, as do those involving a consonant-vowel transposition as compared to those involving two consonants or two vowels (Blythe, Johnson, Liversedge, & Rayner, 2014). Thus, overtly presented transposed letter nonwords elicit longer reading times relative to correctly spelled words, with the magnitude of this increase indexing the amount of increased difficulty in recognition caused by the particular misspelling. However, many of these studies did not manipulate the placement of transposed letters relative to morpheme boundaries (cf., Luke & Christianson, 2013, 2015), and none have done so in English compound words. As such, the question of whether between-morpheme TLs will elicit longer reading times than within-morpheme TLs in English compound words remains unanswered and will be addressed in the current investigation.

Experiment 1

In Experiment 1, we ask whether English compound words containing between-morpheme letter transpositions elicit longer reading times than those containing within-morpheme TLs when they appear in a sentence context. At the broadest level, we predict that reading times for all words containing letter transpositions will be longer than correctly spelled words. More specifically, based on Christianson et al. (2005), we expect to find longer reading times for between- versus within-morpheme letter transpositions, which would provide evidence in favor of obligatory morphological decomposition of compound words. Two other transposition conditions were included to test the severity of the across-morpheme disruption. Following White et al. (2008), readers also saw word-initial and word-final transpositions, both of which have been shown to elicit longer reading times than word-internal transpositions. If readers do indeed decompose compound words into their constituent morphemes, then transpositions located at the word's morpheme boundary may be perceived more like word-external transpositions, producing equally long reading times with this condition. However, in contrast to White et al. (2008), only the target compound word will contain a letter transposition; the rest of the words in the sentence will be spelled normally, in order to test the impact of a single TL word.

Method

Participants—Twenty-five undergraduates from the University of Illinois participated for class credit, or payment of $7. All participants were native English speakers.

Apparatus—Eye movements were recorded via an SR Research Ltd. Eyelink 1000/2000 eye tracker, which records the position of the reader's eye once every millisecond (1000 Hz sampling rate), and has a spatial resolution of less than a character. Text was displayed in 12-point Courier New font. Participants were seated 69 cm away from a 20-inch monitor. At this distance, approximately 3.5 characters subtended 1° of visual angle. Head movements were minimized with chin and head rests. Although viewing was binocular, eye movements were recorded from the right eye only.

Materials and Design—Target words consisted of 49 compound words, ranging in length from seven to nine letters (20 seven-letter words, 22 eight-letter words, and seven nine-letter words), with an average of 7.7 letters. Roughly half of the compounds (24) had two internal consonants (C-C; e.g., *cu**pc**ake*), 12 of which had a three-letter initial morpheme (e.g., ***air****plane*) and 12 of which had a four-letter initial morpheme (e.g., ***rain****coat*). The remaining 25 compounds had three internal consonants, of which 12 words had an initial morpheme that ended in a single consonant and a final morpheme that started with a two-consonant cluster (C-CC; e.g., *su**nsh**ine*). The other 13 words had the opposite pattern, with initial morphemes ending in a two-consonant cluster and final morphemes beginning with a single consonant (CC-C; e.g., *ja**ck**pot*). The average whole word frequency of the compounds, taken from the CELEX database (http://celex.mpi.nl/) was 5.57 appearances per million (range 0–64). The written frequencies of the compound word's first morpheme (average 106, range: 0–456) and second morpheme (average 86, range: 0–456) did not differ, as confirmed by a paired-sample t-test, $t(48)=.94$, $p=.35$.

The compound words could appear in five different transposition conditions: identical control, word-initial transposition, between-morpheme transposition, within-morpheme transposition, or word-final transposition (see Table 1). Letter transpositions always involved adjacent letters, and never produced real words. For word-initial transpositions, the first and second letters of the word were inverted (e.g., ***uc****pcake*), and word-final transpositions involved the last two letters of the word (e.g., *cupca**ek***). The between-morpheme transpositions always involved the inversion of the last letter of the first morpheme with the first letter of the second morpheme (e.g., *cucpake*). Within-morpheme transpositions involved either the last two letters of the first morpheme (for CC-C words, and C-C words with four-letter initial morphemes), or the first two letters of the second morpheme (for C-CC words, and C-C words with three-letter initial morphemes). Thus, the within-morpheme transposition appeared equally in the first and second morpheme across the set of compound words, and always involved either the third/fourth or fourth/fifth letters of the word. The frequencies of the bigrams involved in these TL manipulations did not differ for the word-initial transposition (original: 3051 TL: 2914), t(48)=0.50, p=.62) or between-morpheme TL conditions (original: 1227 TL: 940), t(48)=0.98, p=.33). There were, however, significant differences between the original and transposed bigram frequencies for the within-morpheme TL (original: 3556 TL: 2172), t(48)=5.32, p<.001) and word-final TL conditions (original: 3874 TL: 3251), t(48)=2.60, p=.01). A full list of all items appears in Appendix A.

The critical compound words were presented in sentence frames for which the target word had a very low cloze probability. To ensure that the target words were not predictable, a norming study was conducted in which ten subjects (who did not participate in the eye-tracking portion) were presented with the sentence frame up to the critical word and were asked to complete the sentence. For forty-one of the sentences, no participant completed the sentence with the correct compound word. The eight sentences that at least one participant completed with the target compound word were rewritten, and were judged by three native English speakers to not be predictive of the target word. The sentences contained 12 words on average (range: 8–16 words). The critical compound word, which was the only word misspelled in the sentence, never appeared as the first or last word of the sentence (average: word 6; range: 3–10). Every subject read all 49 critical sentences, with 9–10 appearing in each experimental condition.

Procedure—After signing informed consent, each participant's eye movements were calibrated using a 9-point calibration screen. In the testing session, each trial involved the following sequence: trials began with a gaze trigger, consisting of a black circle presented in the position of the first character of the text. Once a stable fixation had been detected on the gaze trigger, the sentence was presented in full. The participant pressed a button on a standard game controller to indicate that s/he had finished reading the sentence. At this point, the sentence disappeared. A question about the content of the sentence appeared after 16 of the 49 critical sentences, which participants answered by pressing the appropriate button on the controller. The question never referred to the critical compound word. After the comprehension question, the next trial began again with the gaze trigger. Sentences were presented in a random order for each participant. In addition to the 49 experimental trials, each list contained 105 other sentences with a variety of structures, and comprehension questions were asked after approximately 34 of these filler sentences as well.

Data Analysis—Within the Eyelink 1000 data analysis package, consecutive fixations shorter than 80 ms and less than 0.5° apart were merged into a single fixation, while other fixations shorter than 80 ms were deleted from analysis. In addition, fixations longer than 800 ms were also deleted from the analysis because these typically indicate track loss. Less than 3.6% of trials were excluded due to track loss or skipping of the critical compound word.

Results

Behavioral Results—Participants performed well on the comprehension questions, with an average accuracy of 85.6%. Because there were no *a priori* predictions about how misspellings might affect comprehension question accuracy, an omnibus repeated measures ANOVA was conducted on the accuracy data comparing all five conditions against one another. Results showed a marginal effect of transposition condition, $F(4,96)=2.22$, $p=.07$. This marginal effect likely reflects the fact that comprehension scores in the word-initial TL condition (79% accurate) were low relative to the other four conditions, which were all above 85% and relatively similar to each other (word-final: 93%, control: 86%, within-morpheme TL: 88%, between-morpheme TL: 92%).

Eye-tracking Results—Reading times on the target compound word were analyzed as a function of the type of transposition the word contained. We examined five standard reading time measures: first fixation duration (the length of a reader's first fixation on the word in first pass reading), single fixation duration (the length of a fixation when it is the only fixation on that word), gaze duration (the sum of all fixations made on a word during the first pass, before leaving it in either direction), go-past time or regression path duration (a right-bounded measure, including all fixations from the time the reader first lands on the word in the first pass until they move past it to the right, including regressions back in the text), and total time (the sum of all fixations on a word).

Trial-level reading times were submitted to linear mixed effects regression (LMER) modeling, using the lme4 package (Bates, Maechler, Bolker, & Walker, 2014) in R (R Core Team, 2014). Misspelling condition was included as a fixed effect. Contrasts were constructed to test planned comparisons between conditions, and were defined as follows: Contrast 1 (C1) tested the Control (No TL) vs. all TL conditions (overall effect of misspelling), Contrast 2 (C2) tested word-external TLs vs. word-internal TLs, Contrast 3 (C3) tested between-morpheme TLs vs. within-morpheme TLs, and Contrast 4 (C4) tested word-initial TLs vs. word-final TLs. Separate models were run for each of the five reading time measures. Models were fit with the maximal random effects structure (Barr, Levy, Scheepers, & Tily, 2013), which entailed including random slopes and intercepts for the spelling condition factor by both subjects and items. For models that failed to converge with the maximal random effects structure (all but single fixation duration go-past time), a backwards-stepping procedure was employed to find the maximal random effects structure that would converge. The final models included the following random effects structures: first fixation duration had no correlations between slopes and intercepts for the subjects and items error terms; gaze duration had no correlation between slopes and intercepts for the by-subjects slopes; total time had no random slopes for the by-items error terms.[1] A contrast was considered significant if the absolute value of its associated t-value exceeded $|2|$. All

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[1] It should be noted that the pattern of effects observed in the model outcomes did not differ for these final models and those seen in intercepts-only models created for each reading time measure.

models were conducted on raw reading times. Models analyzing log reading times produced identical results, and so for ease of interpretation, we report the models on untransformed reading times.

Mean reading times are listed in Table 2, and the outcomes of the LMER models are listed in Table 3. The first contrast, comparing the control condition to the mean of all of the TL conditions, was significant for every reading measure except single fixation duration. This is unsurprising, and indicates that encountering a misspelling elicited longer reading times compared to correctly spelled control words. The next contrast comparing the word-external to word-internal transpositions was significant for all reading time measures except first fixation duration. This finding replicates prior work (White et al., 2008) in showing that external transpositions are more disruptive to reading times than internal transpositions, but with first fixation effects that do not reach significance. The contrast comparing word-initial versus word-final transpositions was significant for all reading time measures except for single fixation duration, replicating previous work that word-initial TLs are more detrimental to word recognition than word-final TLs. Finally, the critical contrast comparing the between- versus within-morpheme letter transpositions was not significant for any reading time measure (all $t<|1.19|$), indicating that there were no significant reading time differences between these two conditions.

Discussion

Experiment 1 investigated the online processing consequences elicited by compound words containing letter transpositions during sentence reading. Unsurprisingly, words containing letter transpositions produced longer reading times than words without letter transpositions, replicating previous eye-tracking work (Blythe et al., 2014; Rayner et al., 2006; White et al., 2008). However, findings did not support predictions from Christianson et al. (2005) that between-morpheme TLs would produce greater disruption to reading times than within-morpheme TLs. Instead, these two conditions elicited equally large reading time costs, and importantly, these were *smaller* than those elicited by word-external transpositions, further suggesting that the constituent morphemes were not recognized separately. This study provides the first evidence that readers do not engage in obligatory morphological decomposition of compound words during sentence reading. These eye-tracking data cannot speak to whether the constituent morphemes may have eventually been activated via top-down support from the morpho-semantic processing route. However, we have no evidence that readers treated these two transposition conditions differently on any eye-tracking measure.

Experiment 2

The findings from Experiment 1 indicate that between- and within-morpheme letter transpositions in compound words produce equally long reading times when they appear in a sentence context. It could be the case, however, that the language comprehension system did in fact appreciate the difference between these two conditions, but in a way that did not affect eye movements. As such, in Experiment 2, we ask whether between- and within-morpheme letter transpositions elicit distinguishable ERP effects, which would indicate differential engagement of underlying neural systems by these two conditions.

Because of their multidimensional nature, ERPs are a useful tool for measuring the TL similarity effect. ERPs provide information about the timing, polarity, and scalp distribution of effects generated by an input stimulus with millisecond level accuracy, so they can be used to observe how processing of a target word unfolds over time. ERPs are elicited obligatorily, meaning that participants do not have to engage in a secondary task, such as lexical decision or naming aloud, to generate a response. This feature is particularly advantageous to test the hypothesis that two conditions that elicit similar end state measures – such as the equally long reading times observed for by within- and between-morpheme TLs in Experiment 1– could in fact be driven by different underlying neural mechanisms.

We will situate Experiment 2 by first briefly reviewing the existing evidence from the neuroimaging literature on general effects of morphological decomposition. Next, we will address the ERP literature on transposed letter processing more generally, and finally, we will describe effects elicited by misspelled words embedded in sentence contexts, to better inform our predictions about the current experiment.

Neuroimaging Studies of Morphological Decomposition

Findings from the neuroimaging literature regarding the neural underpinnings of morphological decomposition are mixed at best. Individual effects seem to depend heavily on the type of affix used (inflectional, derivational, or compound words), the presence of a prime (as compared to overt processing), whether the words were presented acoustically or visually, and the type of task employed. With respect to inflectional morphology, there is consistent evidence from ERPs (Münte, Say, Clahsen, Schiltz, & Kutas, 1999), fMRI (Tyler, Bright, Fletcher, Stamatakis, 2004; Tyler, Stamatakis, Post, Randall, & Marslen-Wilson, 2005) and patient work (Tyler, Marslen-Wilson, Stamatakis, 2005) that inflected verbs undergo morphological decomposition. Specifically, the left inferior frontal gyrus (LIFG) has been found to be more active when processing regular versus irregular verb forms, and damage to this area selectively impairs the processing of regular but not irregular verbs (i.e., only those that can easily undergo morphological decomposition), suggesting that this brain area is involved in the decomposition of inflected verb forms.

The findings regarding derivational morphology are less straightforward. Many studies using ERPs, MEG, and fMRI have attempted to understand how certain prime types (morphologically transparent, morphologically opaque, orthographic, and semantic) facilitate stem processing, on the assumption that if the prime underwent decomposition that it would provide more facilitation to its stem. However, there is a lack of consistency across studies, both in design and outcome, rendering conclusions difficult. One consistent finding across studies is that the N400 component, an ERP response associated with the initial semantic processing of words (for a review, see Kutas & Federmeier, 2011), exhibits facilitation from morphologically transparent primes (Barber, Dominguez, & de Vega, 2002; Lavric, Clapp, & Rastle, 2007; Lavric, Rastle, & Clapp, 2011; Morris, Frank, Grainger, & Holcomb, 2007; Morris, Grainger, & Holcomb, 2008). However, N400 facilitation following other types of primes is less clear: sometimes there is equal facilitation for both morphologically transparent and opaque words (Lavric, et al. 2007), but sometimes opaque priming is less robust (Morris et al., 2007) and exhibits different timing and/or scalp topography (Barber et al., 2001; Lavric et al., 2011), and also sometimes orthographic form priming is present as well (Lavric et al., 2007) in a manner that is graded with transparency (Morris et al., 2007). Some work from the behavioral literature suggests that orthographic form priming effects depend on the lexicality of the prime, with nonwords producing robust stem priming regardless of the status of the affix (flexify-FLEX, flexint-FLEX, Beyersmann, Cavalli, 2016) but real words failing to produce form priming (cashew-CASH, Beyersmann, Ziegler, 2016). Whether these behavioral priming effects would also replicate in N400 priming effects remains an open question.

Effects of morphological priming may be more consistently observed in a time window earlier than the N400. Some ERP work has found priming in the window of the N250 ERP component (Beyersmann, Iakimova, Ziegler, & Cole, 2014; Morris, et al., 2007; Morris, et al., 2008; Lavric, Elchlepp, & Rastle, 2012), which is thought to reflect the mapping from sublexical to whole-word forms (Grainger & Holcomb, 2009). Converging work from the MEG literature suggests that the language processing system may be sensitive to apparent morphological structure within this time window, as the M170 component (which has been linked to letter string processing, Tarkiainen, Helenius, Hansen, Corneliseen, & Salmelin, 1999) is modulated by morphological manipulations (Solomyak & Marantz, 2010; Zweig & Pylkkänen, 2009). Further, some work from the fMRI literature has found that certain left hemisphere brain areas involved in language comprehension show unique deactivation following morphological primes, such as the anterior middle occipital gyrus (Gold & Rastle, 2007) as well as the left inferior frontal gyrus (Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007). Again, however, these results are not always consistent, as Devlin, Jamison, Matthews, and Gonnerman (2007) found a total overlap between areas exhibiting morphological priming and those showing orthographic priming (the left occipitotemporal cortex) and semantic priming (the left angular gyrus). In sum, the answer to the question of whether words containing derivational affixes engage different underlying neural processing when viewed in a primed lexical decision paradigm seems to be “most likely, yes,” although there is still much debate as to whether this decomposition process operates independently of semantics (Beyersmann et al., 2014), or whether semantics affects early (Morris et al., 2007) or later (Lavric et al., 2011) aspects of this process.

ERP Effects of Compound Word Processing

Studies of visually presented compound words find generally larger N400 responses for compound words versus monomorphemic words (which could, however, potentially be a confound of concreteness; Fiorentino, Naito-Billen, Bost, & Fund-Reznicek, 2014). N400 responses to compound words have also been shown to be sensitive to constituent frequency (Vergara-Martínez, Perea, Gomez, & Swaab, 2013) and constituent lexicality (El Yagoubi, Chiarelli, Mondini, Danieli, & Semanza, 2008; c.f. Coch, Bares, & Landers, 2013). Converging evidence from MEG has found that the M350 component (which is sensitive to lexico-semantic factors, and is believed to contribute to the N400; Pylkkanen & Marantz, 2003) is also sensitive to constituent frequency in compound words (Fiorentino & Poeppel, 2007) and stem frequency in derived words (Solomyak & Marantz, 2009). Together, then, these findings suggest that each constituent of a compound word may exert at least partially separable effects on brain activity during visual recognition, providing evidence the whole-word recognition is mediated by morphological decomposition.

There is one important caveat to note, however: the vast majority of the studies investigating morphological decomposition involved words presented in either a priming paradigm or in isolation. Only one prior ERP study examined responses to compound words in sentences (Vergara-Martínez et al., 2009), and those words appeared sentence-initially and so lacked the preceding message-level meaning provided by our moderately constraining sentences. Given that the presence of a sentence context can mitigate even robust ERP effects of frequency (Van Petten, 1993) and reading time effects of compound-word constituent transparency and frequency (Frisson, Niswander-Kelment, & Pollatsek, 2008; Juhasz, 2012; Pollatsek & Hyönä, 2005), it seems possible that the previously observed effects of morphological decomposition could be different – or absent – when compound words are processed with contextual support.

TL Effects in ERPs

A number of ERP studies have investigated the processing consequences of letter transpositions through the masked priming paradigm, and these have generally replicated the behavioral literature in showing facilitated processing following transposed letter versus replacement letter primes. Specifically, the N250 component was reduced following TL versus RL primes in two different studies (Duñabeitia, Molinaro, Laka, Estévez, & Carreiras, 2009; Grainger, Kiyonaga, & Holcomb, 2006), suggesting easier orthographic processing following TL primes. Other studies have found that the N400 component is also reduced following TL versus RL primes (Carreiras, Gillon-Dowens, Vergara, & Perea, 2009; Vergara-Martínez, Perea, Marín, & Carreiras, 2011), indicating that TL primes facilitate access to the word's representation in semantic memory better than do RL primes. Finally, in a related pair of studies in which single words were fully viewed (without primes), TL nonwords again elicited facilitated N400 amplitudes relative to RL nonwords (Carrerias, Vergara, Perea, 2007), an effect that was more pronounced for higher frequency words (Vergara-Martínez et al., 2013). Together, then, the ERP evidence mirrors behavioral findings in showing that both orthographic and semantic processing are facilitated following TL versus RL nonwords and primes.

ERPs and Misspellings During Sentence Reading

Work has also been done to investigate the ERP consequences of encountering misspelled words in a sentence context (although no study has explicitly used transposed letter nonwords). In general, misspelled words in sentences elicit a late posterior positivity, or P600 component, beginning roughly 500 ms after target onset, with a scalp distribution largely focused over posterior electrode sites. This effect has been elicited by letter addition misspellings (i.e., *broome* for *broom*; Münte, Heinze, Matzke, Wieringa, & Johannes, 1998) and pseudohomophones of target words (i.e., *bouks* for *books*; Van de Meerendonk, Indefrey, Chwilla, & Kolk, 2011; Vissers, Chwilla, and Kolk, & 2006). Furthermore, the size of the P600 elicited by the misspelling has been found to be bigger for expected than unexpected words, and absent for anomalous words. The graded nature of this effect suggests that the size of the P600 indicates the severity of the spelling violation with respect to readers' ongoing predictions, as we know that readers predict even the orthographic form of expected words in highly constraining sentences (Laszlo & Federmeier, 2009).

In sum, spelling errors (at least single-letter additions or replacements) elicit late posterior positive components, which are graded based on the difficulty imposed by the particular misspelling. However, no ERP study has employed the classic transposed letter effect during sentence reading, and especially not with respect to morpheme boundaries in compound words. As such, in Experiment 2, we will address this current gap in the literature to assess the type of ERP processing consequences elicited by within- and across-morpheme letter transpositions. We predict that if across-morpheme letter transpositions cause more difficulties for readers, as would be predicted by accounts of morphological decomposition and the results of Christianson et al. (2005) and accounts of obligatory morpho-orthographic decomposition of complex words, then this condition will elicit bigger (more positive) P600 components than within-morpheme letter transpositions. On the other hand, if compound words can be recognized via a whole-word route during sentence reading, as suggested by our findings from Experiment 1, we would instead predict that these words will elicit equally large P600 components that do not differ for the between- and within-TL conditions. We will also include a set of length- and frequency-matched non-compound words, embedded in similarly constraining sentence contexts and with letter transpositions in similar locations, to ask whether the P600 elicited by these words differs in amplitude from that elicited by the compound words. If readers perceive morpheme boundaries as being more similar to word-external letter locations, we would expect that TLs in the compound words would be more disruptive than those in non-compound words, thus producing larger amplitude P600 components.

A secondary question we can ask from this dataset is whether either TL condition results in differential N400 effects compared to correctly spelled words, which would indicate that the TL nonwords allowed for less effective contact with semantics (Kutas & Federmeier, 2011). Previous studies have found that non-words created by swapping or replacing parts of compound words generate N400 lexicality effects (i.e., more negative N400s than real words) (El Yagoubi et al., 2008). Based on this, we would predict that if readers must access each morpheme of the compound word separately to achieve word recognition, then the between-morpheme TL condition would produce larger N400 lexicality effects than the within-morpheme TL condition, because the TL-between condition would create *two* nonword constituents (e.g., *cupcake* would become *cuc* and *pake*), whereas the TL-within condition would only produce *one* nonwords constituent (e.g., *cupcake* would become *cup* and *acke*).

Methods

Participants—Twenty-one University of Illinois undergraduates participated in the study for course credit (12 males, 8 females; mean age: 19, range: 18–23). All were native English speakers, with no consistent exposure to other languages before the age of five. Subjects did not have a history of neurological disorder or defect. All were right-handed as assessed by the Edinburgh Inventory (Oldfield, 1979), and 13 reported having left-handed family members.

Materials—Two different types of target words were each embedded in sentences: compound words (n=90) and non-compound words (n=50). The compound words were on average 7.9 letters long (range: 7–10), with an average whole-word frequency of 4.5 per million (range: 0–64) (from Celex lexical database, http://celex.mpi.nl/). The written frequencies of the compound word's first morpheme (mean: 104; range: 0–1093) and second morphemes (mean: 122; range: 0–1147) did not differ significantly, $t(89)=-.62$, $p=.54$. The frequency of the critical bigram at the morpheme boundary did not differ between the correctly-spelled and TL-between condition (correct: 1081 TL: 1068), $t(89)=.07$, p=.94), although the frequency of the bigram involved in the TL-within manipulation was significantly lower in the misspelled condition (original: 3358 TL: 2222), $t(89)=5.83$, p<.001). The compound words had an average neighborhood size of 0.19 (range: 0–2). In their misspelled conditions, the TL-between compounds had an average neighborhood size of 0.02 (range: 0–1), and the TL-within compounds had an average neighborhood size of 0.03 (range: 0–1). The non-compound words were on average 8 letters long (range: 7–10), with an average word frequency of 6.29 per million (range: 0–15) and average neighborhood size of 0.85 (range: 0–7). In their misspelled conditions, the non-compound words had an average neighborhood size of 0.03 (range: 0–2). A full list of compound items can be found in Appendix B.1, and the non-compound items are listed in Appendix B.2.

The only lexical-level factor that differed significantly between the compound and non-compound words was concreteness. This was determined by a norming study, in which 12 undergraduates, drawn from the same subject pool but who did not participate in the ERP portion of the study, rated the set of 140 compound and non-compound target words on the degree to which they felt that the word could be experienced by the senses, with 7 being "highly concrete" and 1 being "less concrete." We also included 140 filler words (70 of which were highly concrete, and 70 of which were highly abstract), producing a total of 280 items for participants to rate. Compound words were on average rated as more concrete (average: 5.4) than the non-compound target words (average: 4.6), a difference that was found to be significant, $F(1,139)=12.97$, $p<.001$.

Both types of words appeared in sentences in which they were plausible and only moderately predictable from the sentence context. In order to control the plausibility and expectancy of the target compound words with respect to their sentence frames, a norming study was conducted with a separate group of 28 undergraduates, also drawn from the same subject pool as the current study and who did not participate in the ERP portion. We started with 122 compound words, each of which of which was embedded in two different sentences: one plausible and the other implausible. The implausible stimuli were created by swapping the compound words between sentences, such that the same sentence frames and target words would constitute the plausible and implausible conditions, but in different pairings. These 244 sentences were then divided into two lists, with the constraint that each compound word appeared only once per list and that half of the sentences in each list were plausible. Each participant in the norming study received only one list, meaning that each participant rated 122 sentences (61 plausible, 61 implausible) and that each individual sentence was rated by 14 different participants. The entire sentence was presented to participants with the compound word present, appearing sentence-medially and underlined to highlight it as a target word. Participants were instructed to rate each sentence in two ways. First, they rated the expectancy of the underlined target on a scale from 0–100, with 0 being "not expected at all" and 100 being "completely expected." Participants also rated the plausibility of the entire sentence, again on a scale from 0–100, with 0 being "not plausible at all" and 100 being "completely plausible." From the pool of 122 plausible sentences, we chose 90 to use in the current study, for which the rated expectancy of the target word fell between 40–70 (mean: 54.2; range: 40.3–70.7), and the plausibility was high (average: 96; range: 78.2–100). The final set of 90 sentences was on average 12.9 words long (range: 8–17), and the compound word was never the first or last word in the sentence (average: 5.9; range: 3–11).

The non-compound target words were also embedded sentence-medially in moderately constraining sentences. These sentences were drawn from a previously normed set of materials in which subjects filled in the last word of the sentence in a cloze-norming task (see Federmeier, Wlotko, De Ochoa-DeWald, & Kutas, 2007, for details). The cloze probability of the sentence-final word was moderate, with an average of .46 on a scale of 0–1 (range of .12–.70). Although the expectancy of the target itself was not normed, it was not part of a highly constraining sentence, and, as such, its own cloze probability was likely lower than that of the sentence-final word.

Target words could appear either as correctly spelled or misspelled with a letter transposition. For the compound words, the letter transposition could either occur within one of the word's morphemes or across the morpheme boundary. The between-morpheme transpositions always involved the last letter for the first morpheme and first letter of the second morpheme (i.e., *backyard* to *bacykard*). Half of the within-morpheme transpositions involved the last two letters of the first morpheme (i.e., *raincoat* to *ranicoat*), and the other half involved the first two letters of the second morpheme (i.e., *starfish* to *starifsh*). The within-morpheme transpositions were randomly assigned to the first or second morpheme, with the constraint that if one of the word's morphemes contained only three letters, the other (longer) morpheme would receive in the letter transposition. Each subject saw all 90 critical compound words, 30 in their correctly spelled form, 30 with a between-morpheme letter transposition, and 30 with a within-morpheme letter transposition (15 in the first morpheme, 15 in the second morpheme). Subjects also saw all 50 of the non-compound filler words, 16–17 of which were correctly spelled, and 33–34 of which had a letter transposition. As with the compound words, two different transposed letter versions were created for each non-compound target. While we chose as many monomorphemic non-compound words as possible, due to the nature of the English language, 32 of the filler words had a suffix (typically the inflectional suffixes *–s, -ed*, or the derivational suffixes *–er* or *-or*). Importantly, however, the letter transpositions in these words did not cross the morpheme boundary, and stem-internal transpositions in suffixed words have been shown to produce equal TL priming to identity primes (Luke & Christianson, 2013). In total, each subject read 140 sentences, 93–94 of which contained a single misspelled target word (60 misspelled compound words, and 33–34 misspelled non-compound words), and the remaining 46–47 of which contained all correctly spelled words.

Procedure—Participants were seated 100 cm away from a 21" computer monitor in a dim, quiet testing room. They were given verbal instructions before the experiment started to remain as still as possible with their eyes fixated in the center of the screen and to try to minimize blinks throughout the experiment. Participants were instructed to read for comprehension, and that there would be a memory test on what they read at the end of the experiment. Furthermore, they were told that they might see a few misspellings, but that they should just focus on understanding the sentence to the best of their abilities. Each trial started with the presentation for a string of fixation crosses ("++++") for 500 ms. This was followed by a blank screen for a range of time between 500–1500 ms (jittered to prevent the build-up of slow anticipatory potentials; Walter, Cooper, Aldridge, McCallum, & Winter, 1964), after which a sentence was presented word-by-word in the center of the screen in normal sentence case. Each word was presented in yellow font on a black background, and was on the screen for 200 ms, followed by a 300 ms blank interval (SOA=500 ms). Sentences were followed by a 2000 ms blank screen, after which time the fixation crosses appeared and the next trial began. As previously stated, participants were encouraged to minimize blinks during sentence presentation, but no specified "blink interval" was employed. The experiment was divided into four blocks of 35 trials each, each lasting about six minutes. Between each block, participants received a small break.

At the end of the experiment, a paper-and-pencil memory test was conducted to test subjects' memory for the compound words. A list of 180 correctly spelled compound words was given to each subject, including all 90 target words from the study as well as 90 new compounds. For each word, subjects first indicated whether it had appeared in the study or not. For the words they marked as having seen before, they also indicated whether or not it was spelled correctly when it appeared in the study.

EEG Recording and data analysis—The electroencephalogram (EEG) was recorded from 26 evenly-spaced silver/silver-chloride electrodes attached to an elastic cap. All scalp electrodes were referenced on-line to the left mastoid, and re-referenced off-line to the average of the left and right mastoids. One electrode was placed on the left infraorbital ridge, and referenced to the left mastoid, to monitor for vertical eye movements and blinks. Two electrodes were also placed on the outer canthus of each eye, referenced to each other, to monitor for horizontal eye movements. Electrode impedances for the three electrodes on the face were kept below 10kΩ, and impedances for scalp electrodes were kept below 5kΩ. The continuous EEG was amplified through a bandpass filter of 0.02–100Hz and recorded to hard disk at a sampling rate of 250Hz.

Epochs of EEG data were taken from 100 ms before stimulus onset to 920 ms post-stimulus. Those containing artifacts from amplifier blocking, signal drift, eye movements, eye blinks, or muscle activity were rejected off-line before averaging, using thresholds selected for each participant through visual inspection of the data. Trial loss averaged 8.6%. Artifact-free ERPs were averaged by stimulus type after subtraction of the 100 ms pre-stimulus baseline. Prior to statistical analyses, ERPs were digitally filtered with a low-pass filter of 30Hz.

Results

Behavioral Data—Behavioral results were analyzed from the paper and pencil memory test conducted at the end of the study. Overall, subjects were 67% accurate on the memory test, and specifically recognized 80% of the "old" compound words as having been seen before. Memory performance was assessed with the discriminability index *d'*, with average scores and standard deviations shown in Table 4. This analysis divided responses into three levels based on the word's original spelling in the reading portion (i.e., whether it appeared with a within-morpheme transposition, a between-morpheme transposition, or as correctly spelled). Analyses revealed that memory for the two transposed letter conditions was better than that for words that had originally been viewed as correctly spelled. This pattern was supported by a one-way within-subjects Analysis of Variance (ANOVA), which revealed a significant effect of spelling condition, $F(2,40)=6.43$, $p<.001$. Follow-up paired samples tests confirmed that *d'* scores were higher for both misspelling conditions compared to control (TL-between vs. control, $t(20)=3.34$, $p<.001$; TL-within vs. control, $t(20)=2.82$, $p=.01$), but that they did not differ from each other ($t(20)=.35$, $p=.73$).

We also calculated the percentage of words correctly classified as having been misspelled in the reading portion of the study, *contingent* upon participants having correctly recognizing the word as "old" (see Table 4 for means). Subjects were more accurate in classifying a target as having been correctly spelled than incorrectly spelled, as supported by an ANOVA conducted over the *d'* results, which showed a main effect of spelling condition, $F(2,40)=9.47$, $p<.001$. Paired samples t-tests showed that the correctly spelled words had higher accuracy rates than either of the misspelling conditions (TL-between vs. control, $t(20)=-3.47$, $p<.01$; TL-within vs. control, $t(20)= -3.06$, $p<.001$), which again did not differ from each other ($t(20)=.26$, $p=.79$). Overall, these findings demonstrate that despite showing better recognition of words that originally appeared with a misspelling, participants either did not remember that they were previously misspelled, or there was a bias to report words as having been spelled correctly.

ERP Results—We will present ERP results in two different analysis windows, to address two different questions about the current dataset. First, N400 amplitude will be measured from 300–500 ms post-stimulus onset, to test 1) whether letter transpositions in both compound and non-compound words elicit larger N400 amplitudes than correctly spelled compound words, and 2) whether there is a difference between N400 amplitude elicited by between- and within-morpheme TLs. Secondly, P600 amplitude will be measured from 600–900 ms post-stimulus onset, to test whether 1) TL nonwords will elicit a P600 effect relative to correctly spelled words, and 2) this effect will be bigger for between- versus within-morpheme TLs in compound words[2]. All ANOVAs were conducted using a repeated measures design, with the Greenhouse-Geisser correction for the violation of the assumption

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[2] ERPs were also measured in two earlier time windows: the N250 time window (200–300ms post-stimulus onset), in which previous studies have found effects of masked TL primes (e.g. Duñabeitia, Molinaro, Laka, Estévez, & Carreiras, 2009), as well as P2 time window (150–250ms). Repeated measures ANOVAs conducted over all 26 scalp electrodes comparing the TL-between, TL-within, and control compound word conditions found no effect of spelling condition (N250: $F(2,40)=0.23$, $p=.79$; P2: $F(2,40)=0.20$, $p=.82$) nor interaction with electrode (N250: $F(50,1000)=0.61$, $p=.65$; P2: $F(50,1000)=1.16$, $p=.33$). These results indicate that early perceptual processes were also unaffected by the between- versus within-morpheme TL manipulation.

of sphericity. Electrode will be included as a factor in all ANOVAs, but main effects of electrode will not be reported, as they are not of theoretical significance.

The N400 Time Window: 300–500 ms

Compound words: Mean amplitude of the N400 was measured between 300 and 500 ms over all 26 electrode sites. As shown in Figure 1, the N400 amplitudes elicited by correctly spelled compound words did not differ from those elicited by the transposed letter nonwords. This lack of difference is supported by a one-way within-subjects ANOVA conducted over all electrode sites, which showed a non-significant effect of the factor of spelling (3 levels: TL-between, TL-within, correctly spelled), $F(2,40)=.07$, $p=.93$, and no interaction between spelling and electrode, $F(50,1000)=.59$, $p=.67$.

Non-compound words: As can be seen in Figure 2, no N400 differences were observed between the correctly spelled and TL non-compound words. This was confirmed by an ANOVA conducted over all 26 scalp electrodes, which showed a non-significant effect of spelling (correct vs. TL), $F(1,20)=.27$, $p=.61$, as well as a non-significant interaction between spelling and electrode, $F(25,500)=1.23$, $p=.31$.

The P600 Time Window: 600–900 ms

Compound words: As can be seen in Figure 1, the between- and within-morpheme TL conditions elicited an equally robust positivity relative to correctly spelled compound words from 600–900 ms post-stimulus onset, which was maximal over posterior channels. Results from an ANOVA conducted over all 26 electrode sites confirmed this visual inspection, in showing a main effect of spelling condition, $F(2,40)=6.93$, $p<.01$, as well as a significant interaction between spelling and electrode, $F(50,100)=3.25$, $p<.01$. Next, to explore the topography of this effect, we conducted a distributional analysis over 16 pre-selected channels to equally represent the effects of hemisphere (left or right), laterality (medial or lateral), and anteriority (anterior to posterior). Results showed a main effect of spelling, $F(2,40)=7.13$, $p<.01$, as well a significant interaction between spelling and anteriority, $F(6,120)=25.99$, $p<.05$, indicating that the effect of spelling was bigger at posterior sites. No other effects reached significance (all $F<1.82$, all $p>.10$).

Planned comparisons were conducted to test the critical prediction that the between-morpheme TL condition would elicit bigger P600 amplitudes than the within-morpheme TLs. This comparison was targeted over 15 posterior electrode sites (LMCe, RMCe, LDCe, RDCe, MiCe, MiPa, LLTe, RLTe, LDPa, RDPa, LLOc, RLOc, LMOc, RMOc, & MiOc) where the P600 effects were maximal. Findings showed no difference between the two TL conditions, $F(1,20)=.42$, $p=.52$. Finally, an analysis conducted over the *single channel* that showed the largest P600 difference between the TL-between and TL-within conditions (Middle Occipital) also failed to reach significance, $F(1,20)=1.52$, $p=.23$.

Non-compound words: Letter transpositions in non-compound words also elicited a robust P600 relative to correctly spelled words; as seen in Figure 2, this effect was maximal over posterior sites from 600–900ms. As with the compound words, an analysis over all 26 channel from 600–900 ms found a main effect of spelling, $F(1,20)=8.85$, $p<.01$, which interacted with electrode, *F*(25,500)=4.78, *p*<.01. To better explore the distribution of this positivity, a distributional analysis conducted in the same way as described above found a main effect of spelling, *F*(1,20)=6.98, *p*<.05, as well as interactions between spelling with anteriority, *F*(3,60)=7.77, *p*<.05, and laterality, *F*(1,20)=6.23, *p*<.05. These effects indicate that the P600 amplitude was bigger for posterior relative to anterior sites, as well as for medial relative to lateral sites.

Comparison across word types: A direct comparison between the mean amplitude of P600 elicited by compound and non-compound words is not possible, due to factors that differed between conditions and are known to affect N400 distribution and/or amplitude, such as concreteness (Kounios & Holcomb, 1994) and cloze probability (Kutas & Hillyard, 1984), which could also affect processing in the P600 window. As such, we instead compared the magnitude of the TL *effect* within each word type through the use of difference waves. Difference waves were created by computing a point-by-point subtraction of the waveforms elicited by the transposed letter condition (collapsing across the between- and within-conditions) from those elicited by the correctly spelled condition separately for each word type (i.e., Correct Compound – TL Compound; Correct Non-compound – TL Non-compound). In Figure 3, we can see that both difference waves show an obvious positivity, reflecting the difference between correctly spelled and misspelled words within each word type. This positivity is overlapping at the posterior electrode positions, indicating that this difference is of equal magnitude for the compound and non-compound words. Analyses conducted over the difference waves at the 15 posterior electrode sites confirmed that there was no effect of word type, *F*(1,20)=.09, *p*=.76, nor interaction between word type and electrode, *F*(14,280)=1.17, *p*=.33. These results indicate that there were no differences in the size of the P600 misspelling effect elicited by the two word types.

Discussion

In Experiment 2, participants read sentences including compound words, which could contain within- or across-morpheme letter transpositions, to test for ERP evidence of obligatory morphological decomposition during sentence reading. If readers necessarily recognize compounds via morphological decomposition, then across-morpheme TLs should elicit greater disruption than within-morpheme TLs, specifically in the form of a larger (more positive) P600 component. Findings did not support decomposition: within- and across-morpheme letter transpositions both elicited a larger P600 compared to correctly spelled words, but the amplitude of this late positive component was indistinguishable between the two TL conditions. As a comparison condition, we also included a set of length and frequency matched non-compound words, to test whether transposed letters might be less disruptive when they do not impact morpheme boundaries. However, the results of a difference wave analysis confirmed that the amplitude of the P600 effect elicited by letter transpositions did not differ across these two word types. Our findings replicate previous studies that have also found an LPC/P600 effect to misspelled words in a sentence context (e.g., Van de Meerendonk, et al., 2011; Vissers, et al., 2006). This component is known to be elicited in circumstances in which there is some sort of “reanalysis” or “repair” process that must take place—either due to the presence of overt grammatical errors (Hagoort, Brown, & Groothusen, 1993), garden path sentences (Osterhout & Holcomb, 1992), difficult but grammatical wh-constructions (Gouvea, Phillips, Kazanina, & Poeppel, 2010), or even from musical sequence violations (Patel, Gibson, Ratner, Besson, & Holcomb, 1998). In light of the varied circumstances that can give rise to the P600/late posterior positivity, it has been suggested that it may generally index the ease with which incoming stimuli can be integrated into one's ongoing mental representation (Brouwer, Fitz, & Hoeks, 2012). The fact that the size of this effect was equal for the between- and within-morpheme TLs, as well as for TLs in noncompound words, suggests that this positivity reflected a general difficulty induced by the letter transposition itself, as opposed to a more specific disruption of morphological decomposition.

We also examined N400 amplitude as a measure of the efficiency with which the target stimuli were able to contact the word's meaning in semantic memory. No differences were observed in the N400 amplitude elicited by the TL condition and correctly spelled words, for both the compound and non-compound words. This finding suggests that neither the presence of transposed letters nor their placement relative to morpheme boundaries impeded the reader's ability to access the word's representation in semantic memory. One caveat to these results is that target words in the current study were long (7.9 letters on average) with very small orthographic neighborhood sizes (on average less than one orthographic neighbor per word). For example, the compound word *newspaper* has no orthographic neighbors, nor does its TL-between version, *newpsaper*. We can thus hypothesize that when transposed letter misspellings of words with few orthographic neighbors appear in a sentence context, the contextual support they receive in combination with their sparse orthographic neighborhood produce activation largely for only its base word's representation, eliciting N400 amplitudes that are roughly equal in size as those for the correctly-spelled word.

General Discussion

In two experiments, we asked whether readers engage in obligatory morphological decomposition via morpho-orthographic processing of English compound words encountered in a sentence context. We tested this question through the use of the transposed letter paradigm, with the prediction that, if decomposition plays a vital role in the recognition of compound words, between-morpheme letter transpositions would cause more disruption than within-morpheme letter transpositions, thus generating larger processing costs. We collected two measures of online processing: eye movements elicited during natural sentence reading (Experiment 1), and ERPs elicited during word-by-word sentence reading (Experiment 2). The results of our two experiments were clear: although letter transpositions *did* generate processing costs in both measures, the magnitude of these costs did not differ for the between- and within-morpheme conditions. In general, we replicate previous work showing increased reading times for overt misspellings (Blythe et al., 2014; Johnson & Eisler, 2012; Rayner et al., 2006; White et al., 2008), as well as work showing that misspellings elicit late posterior positivities (Münte et al., 1998; Van de Meerendonk et al., 2011; Vissers et al., 2007). Importantly, however, we find no differences in either reading times or P600 amplitude elicited from the between- and within-morpheme letter transposition conditions. We interpret this as evidence in favor of whole-word recognition of English compound words during sentence reading (the morpho-semantic processing route, as propsed by Diependaele et al., 2009) that does not require readers to decompose words into their morphemes in order to be recognized.

Our findings fail to replicate certain behavioral findings that show greater disruption to processing caused by between- versus within-morpheme TLs, particularly that of Christianson et al. (2005). The current work differs from this, and other, behavioral studies in that readers' only task was to read target words for understanding with the support of a low-to-moderately constraining sentence context, as opposed to responding to a word in isolation (preceded only by a brief prime). One reason for these differences could be task-related: tasks requiring an overt response, especially speeded naming, may show increased sensitivity to the relationship between TL placement and morpheme boundaries. The mechanisms subserving reading aloud are likely very sensitive to letter ordering, particularly when the letters are used in the service of phoneme ordering for speech production (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). On the other hand, mechanisms involved in visual word recognition are largely robust to slight variations in letter ordering, perhaps because of imperfect encoding of letter order, as suggested by current models of letter position coding in visual word recognition (e.g., the SOLAR model: Davis, 2010; the Overlap Model: Gomez, Ratcliff, & Perea, 2008; the SERIOL model; Whitney, 2008). This is supported by the wealth of recent work showing equal stem priming following between- and within-morpheme TLs in lexical decision paradigms (Beyersmann et al., 2012; Beyersmann et al., 2013; Diependaele et al., 2013; Perea & Carreiras, 2006; Rueckl & Rimzhim, 2011). Our results add to this growing literature, and also extend it to the domain of compound words encountered during natural reading.

It is also possible that our moderately constraining sentence contexts may have allowed readers to generate even weak predictions about the compound words that provided enough semantic support for the between-morpheme transpositions to activate their correctly-spelled form better than they did in isolation. Indeed, studies have shown that increasing levels of cloze probability produce graded reductions of both reading times (Rayner & Well, 1996) and N400 amplitudes (Kutas & Hillyard, 1984; Wlotko & Federmeier, 2012) elicited by the expected word. With respect to compound words, even neutral sentence contexts can mitigate the reading time costs associated with opaque versus transparent compound words (Frisson et al., 2008; Pollatsek & Hyönä, 2005), and constraining contexts can eliminate even robust effects of morpheme frequency (Juhasz, 2012). In light of these findings, it is entirely plausible that the larger within- than across-morpheme priming effects found by Christianson et al. (2005) are observable when the words are viewed in isolation, but that the addition of simple sentence contexts in the current experiments helped readers overcome these relatively small costs when the words were encountered during natural reading. Our findings thus help provide a clearer understanding of how readers cope with overtly misspelled words under more typical reading conditions.

Further support for the importance of sentence context in word recognition comes from the fact that in both experiments the within-morpheme TL condition generated bigrams with significantly lower frequency than those in the same position in the correctly spelled words. This difference would be predicted to *increase* the tendency for greater costs from the within- than between-morpheme transpositions if ordered bigram frequency plays a critical role in word recognition (e.g., Whitney, 2008). Our results did not support this prediction, instead showing that readers are not sensitive to bigram frequency, at least when recognizing compound words during sentence reading. These findings could help inform future models of word recognition by demonstrating that precise letter-position coding may be less important in the presence of top-down activation from even moderately constraining sentence contexts.

Finally, it is worth noting that compound words are relatively rare in English, and the process of creating new compound words is less productive than in other languages, such as Finnish or German (Hyönä & Pollatsek, 1998). As such, readers may be less likely to rely on morpho-orthographic decomposition when processing English compound words, especially when these are encountered in a sentence context, which increases the involvement of semantics. On the other hand, English readers seem to rely more heavily on morpho-orthographic processing in the recognition of inflected English words, for which greater between- than with-morpheme TL costs have been observed during sentence reading (Luke & Christianson, 2013, 2015). Given that the contribution of transparency to morphological processing in isolation is still not well defined (Amenta & Crepaldi, 2013), future work is needed to better understand the relationships among transparency, type of morphology (inflectional, derivational, compounding), and top-down effects of sentence context in determining which processes readers engage in to recognize complex words.

The current findings also do not suggest that readers *never* appreciate independent meanings of a compound's morphemes. Diependaele et al.'s (2009) proposal of a morpho-semantic route to accessing complex words suggests that activation spreads in a top-down manner from a whole word's lexical representation to its morphemes after the word has been recognized. It could also be the case that readers activate each constituent despite the transposed letters via the coarse coding of letter positions (Grainger & Ziegler, 2011) or through the underspecification of letter assignment to particular morphemes during recognition (McCormick et al., 2008, 2009). If any of these processes, or some combination of them, is operating to decompose the words into morphemes in parallel with whole-word recognition of the compound words, we found no evidence of it. Across both experiments, our findings provide no indication that the comprehension system ever treated the within- and across-morpheme TL conditions differently, either in terms of reading times or ERPs.

Our lack of evidence for obligatory access to sublexical morphemic units may seem at odds with findings in the literature on compound word processing showing that the meaning of each constituent becomes active at some point during recognition, as indicated by effects of compound constituent frequency on both reading times (Juhasz, Starr, Inhoff, & Placke, 2003; Marelli & Luzzatti, 2012) and N400 amplitude (Vergara-Martínez, et al., 2009), as well as (less robust) effects of transparency on reading times (Pollatsek & Hyönä, 2005). One factor that we did not consider in the current experiment is the transparency of the compounds (or how much the constituent meanings are related to the whole word meaning). There is at least some evidence that transparency may interact with TL priming effects from derived words as well (Diependaele et al., 2013), and with constituent frequency effects in reading times (Amenta et al., 2015). As such, the role of transparency in predicting across-morpheme TL effects on compound word processing in sentence reading remains an open question. One final factor that was not considered in the current experiment was individual reading proficiency. Recent work suggests that more proficient readers may be able to more effectively use opaque or nonword primes to access whole-word representations (Beyersmann, Casalis, et al., 2015, 2016) and that they exhibit different TL effects (Veldre & Andrews, 2015a,b). These findings raise interesting questions about the possible role these factors play in determining the circumstances under which evidence for obligatory morpho-orthographic decomposition is, and is not, observed, and how this information can be used to shape future models of complex word recognition. Work in this vein could help unite the literatures on the morphological processing of compound words and derived/inflected words, which are currently quite separate.

In sum, in two experiments we found that between- and within-morpheme letter transpositions in English compound words produce equal processing costs in both reading time measures (Experiment 1) and the size of the P600 component they elicit (Experiment 2). We thus conclude that these two types of letter transposition cause *general* processing costs relative to correctly spelled words, but that they do not differ from each other. Together, these two pieces of complimentary evidence suggest that English compound words can be comprehended via whole-word recognition in relatively unconstrained contexts during normal silent reading.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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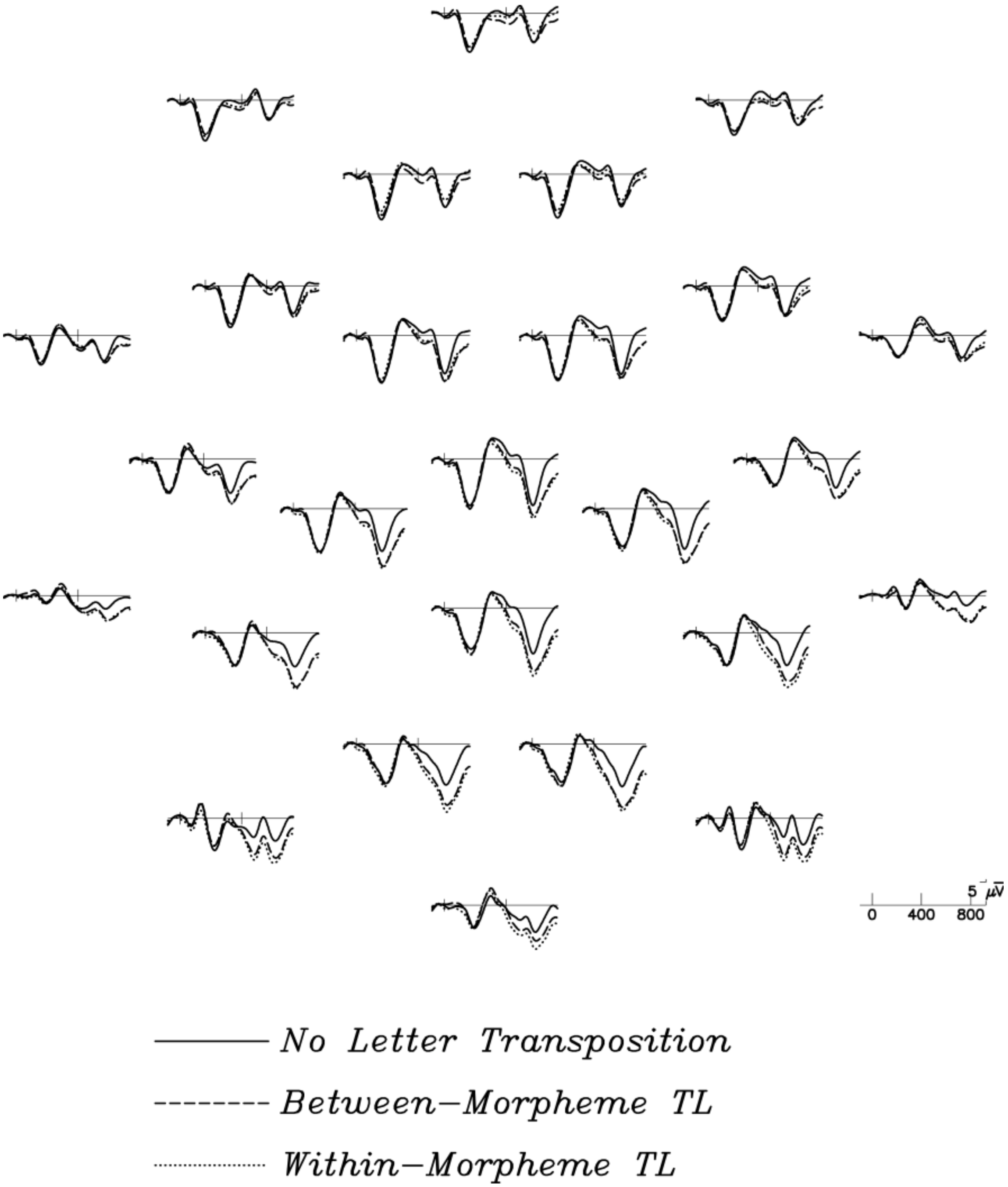

Figure 1.

ERPs from all 26 scalp locations to compound words in the correctly spelled condition (solid lines), between-morpheme TL condition (dashed lines), and within-morpheme TL condition (dotted lines), from target onset to 920 ms post-stimulus onset. Both TL conditions elicit a late posterior positivity, largest from 600–900 ms post-stimulus onset over posterior electrode sites that did not differ in size between these two conditions.

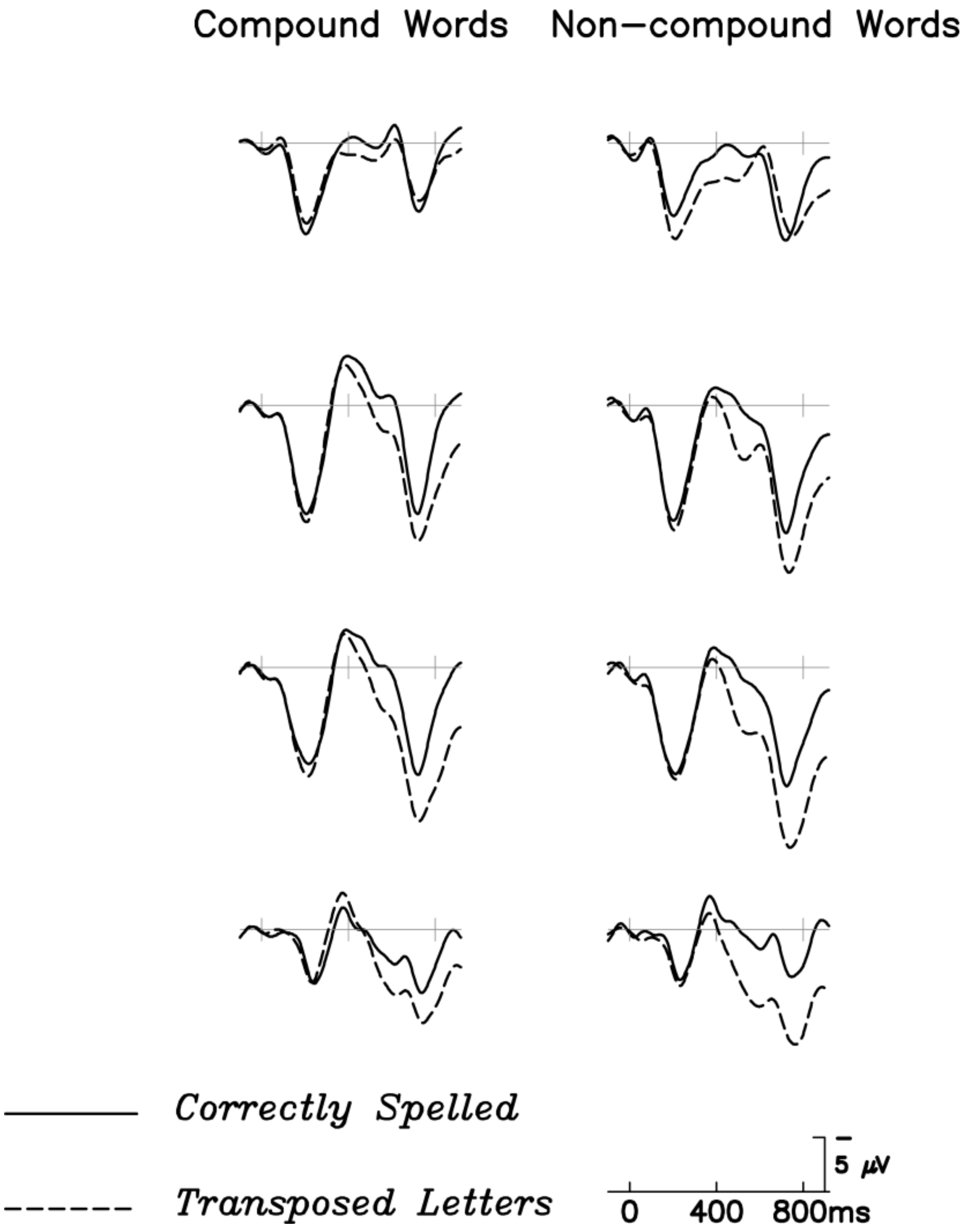

Figure 2.

ERPs to non-compound target words (right) compared to those to compound words (left) in the correctly spelled condition (solid lines) and the TL condition (dashed lines), from target onset until 920 ms post-stimulus onset. Misspellings of both word types elicit a late posterior positivity that is very similar in terms of its onset, magnitude, and distribution.

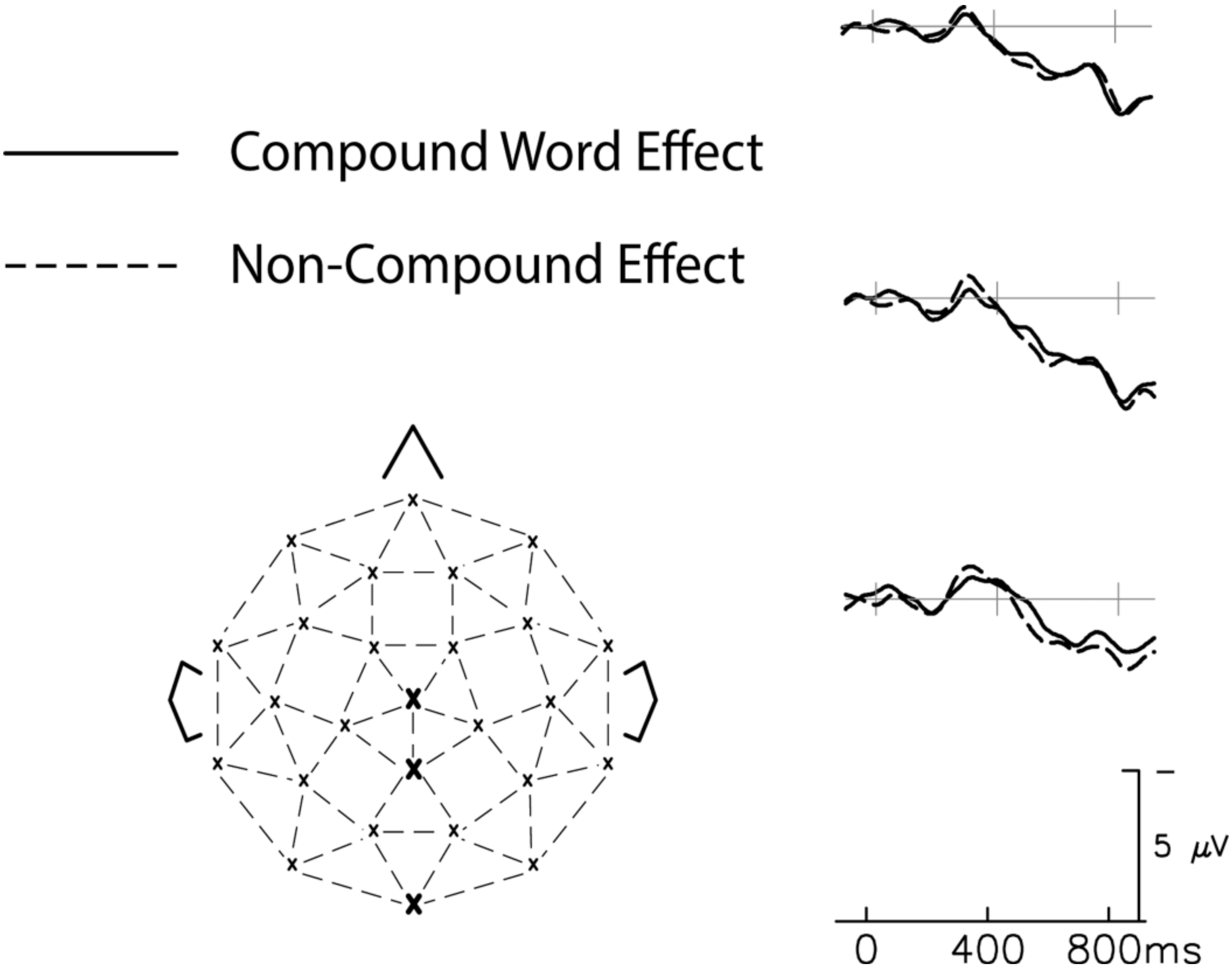

Figure 3.
Difference waves, created by subtracting the waveforms elicited by the transposed letter condition from the correctly spelled condition, for the compound words (solid lines) and the non-compound words (dashed lines), from target onset through 920 ms post-stimulus onset over three posterior channels. The magnitude of the misspelling effect is identical across compound and non-compound words.

Table 1

The five experimental conditions in which target words could appear.

Transposition	C-C	CC-C	C-CC
Identical control	cupcake	jackpot	sunshine
External			
Word-initial	ucpcake	ajckpot	usnshine
Word-final	cupcaek	jackpto	sunshien
Internal			
Between-morpheme	cucpake	jacpkot	susnhine
Within-morpheme	cupacke	jakcpot	sunhsine

C-C = compound words consisting of initial morphemes ending in one consonant and final morphemes beginning with one consonant; CC-C = compound words consisting of initial morphemes ending with two consonants and final morphemes beginning with one consonant; C-CC = compound words with initial morphemes ending in one consonant and final morphemes beginning with two consonants.

Table 2

Mean reading times in ms (and standard deviations) for the compound words.

Transposition Condition	First Fixation	Single Fixation Duration	Gaze Duration	Go-Past Time	Total Time
Control	230 (35)	254 (67)	288 (60)	363 (87)	387 (83)
External					
Word-initial	272 (47)	306 (92)	502 (158)	639 (215)	688 (214)
Word-final	250 (45)	262 (63)	390 (121)	475 (164)	548 (197)
Average	*261(39)*	*290 (72)*	*445 (118)*	*558 (167)*	*620 (187)*
Internal					
Between	248 (47)	260 (66)	350 (94)	456 (191)	445 (113)
Within	255 (44)	240 (67)	348 (87)	406 (131)	447 (118)
Average	*252 (40)*	*251 (57)*	*349 (78)*	*429 (132)*	*446 (107)*

Table 3

LMER model outcomes for reading time measures

Reading Time Measure	Condition Comparison	B	SE	|*t*|
First Fixation Duration	**Intercept**	**250.93**	**7.50**	**33.47**
	Control vs. All TL	**21.44**	**5.67**	**3.78**
	External vs. Internal TL	10.07	7.84	1.28
	Between- vs. Within-Morpheme TL	−7.94	8.96	−0.89
	Initial vs. Final TL	**22.72**	**10.05**	**2.26**
Single Fixation Duration	**Intercept**	**262.51**	**9.82**	**26.73**
	Control vs. All TL	15.22	8.61	1.77
	External vs. Internal TL	**27.94**	**13.35**	**2.09**
	Between- vs. Within-Morpheme TL	13.29	13.54	0.98
	Initial vs. Final TL	37.51	23.39	1.60
Gaze Duration	**Intercept**	**375.85**	**17.69**	**21.25**
	Control vs. All TL	**86.64**	**15.20**	**5.70**
	External vs. Internal TL	**96.51**	**21.31**	**4.53**
	Between- vs. Within-Morpheme TL	−1.13	20.85	−0.05
	Initial vs. Final TL	**111.76**	**31.12**	**3.59**
Go-Past Time	**Intercept**	**467.21**	**25.67**	**18.20**
	Control vs. All TL	**103.04**	**22.77**	**4.53**
	External vs. Internal TL	**127.54**	**28.80**	**4.43**
	Between- vs. Within-Morpheme TL	44.01	37.11	1.19
	Initial vs. Final TL	**159.77**	**39.60**	**4.04**
Total Time	**Intercept**	**503.56**	**26.65**	**18.90**
	Control vs. All TL	**114.40**	**22.68**	**5.04**
	External vs. Internal TL	**172.22**	**28.53**	**6.04**
	Between- vs. Within-Morpheme TL	−6.98	28.51	−0.25
	Initial vs. Final TL	**137.88**	**36.11**	**3.82**

Table 4

Average of d’ (and standard deviations), and percentage of correct spelling judgments on the compound words in the memory test.

Spelling Condition	Average *d’*	% Accurate Spelling Judgments
Between-Morpheme Transposition	1.15 (.46)	40%
Within-Morpheme Transposition	1.12 (.46)	39%
Correctly Spelled	.94 (.41)	73%