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Research report

Decomposition of morphologically complex words in English: evidence from event-related brain potentials

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Abstract

To explain processing differences between regular (e.g., start/started) and irregular (e.g., think/thought) word formation linguistic models posit either a single mechanism handling both morphological clusters or separate mechanisms for regular and irregular words. The purpose of the present study is to investigate how these processing differences map onto brain processes by assessing electrophysiological effects of English past tense forms, using the repetition priming paradigm. Event-related brain potentials (ERPs) were recorded from 59 scalp sites as 19 subjects read stem forms of regular and irregular verbs from a list of 1152 words; the stem forms were either preceded (5–9 intervening items) by their past tense forms (= primed condition) or by past tense forms of unrelated verbs (= unprimed condition). The difference between the ERPs to the primed and unprimed stems was taken as a measure of morphological priming. We found that the ERPs to regular verbs were clearly different from those to irregular verbs: the former were associated with an N400 reduction in the primed condition; primed irregular verb stems, however, showed no such effect. Control conditions demonstrated that the N400 modulation for regular verbs cannot be attributed to formal (i.e., phonological or orthographical) priming. These ERP effects indicate that regular verbs serve as more powerful primes for their corresponding stem forms than irregular past tense forms, suggesting that regular (but not irregular) past tense forms may be decomposed into stem plus affix.

Keywords: Event-related potentials; N400; Inflectional morphology; Priming; Dual route; Connectionism

1. Introduction

One central issue in psycholinguistic research is how the mental grammar might be connected to processes involved in the real-time production and comprehension of language. With respect to morphology, psycholinguists have examined the potential correspondence between the linguist's decomposition of a morphologically complex word and the way it is segmented by the speaker-hearer during online production and comprehension.

Current processing models of morphology provide conflicting answers to this question. Some researchers claim that the morphological structure of words plays no role in the way they are produced or perceived and that morphologically complex words are fully listed in memory [e.g., Refs. [7,36,37]]. Connectionist models are similar in spirit and claim that morphological structure is not explicitly represented in the mental lexicon; rather, morphologically complex words are said to be represented like simple words, through associatively linked orthographic, phonological and semantic codes in terms of activation patterns over units and weighted connections between them [14,56,58,59].

In contrast, several researchers have argued that lexical representations encode morphological structure and that this information plays a role in comprehension and production [12,62,63]. For example, Taft [62,65], Taft and Forster [63], and Taft et al. [64] have argued for a morphological

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decomposition model according to which only stems but not affixed words are stored in memory and in which general decomposition operations such as 'prefix stripping' are carried out whenever possible. Clearly, however, irregularly inflected words such as *sought* and so-called suppletive forms such as *went* are difficult to handle for a full decomposition model.

Other models of morphological processing have combined whole-word based representations with affix-stripping in dual-route models [8,18,33,34,46,57]. Word frequency and phonological transparency seem to be crucial in determining which of the routes is more efficient; frequent phonologically non-transparent words are more likely to have full-form representations than low-frequency transparent words. Gordon [20], for example, found whole-word frequency effects for regular past tense forms that exceed a certain frequency threshold (6 per million); this suggests that while regular inflections are affixation-based, whole-word representations seem to be available in the lexical system, particularly for high-frequency items (cf. also Refs. [1,8] for discussion).

A phenomenon that has received much attention in morphological processing research is English past tense formation. From a linguistic perspective, two qualitatively different mechanisms can be distinguished in past tense formation: (i) a simple lexical look-up of past tense forms stored in the lexicon along with lexical entries for their base forms and (ii) an affixation procedure [27,30,46]. The affixation procedure captures the regular aspects of inflectional morphology as in the past tense *-ed*, e.g., *walked*, which can be easily decomposed into stem + affix and readily extends to novel items. Lexically-based inflection, on the other hand, epitomizes the irregular aspects of inflectional morphology including sublevel regularities among irregular past tense forms of English (*sing–sang*, *ring–rang*, etc.). A parallel distinction may be honored by the brain: If the structural properties of inflected words determine the way they are processed, then we would expect to find signs of morphological decomposition for regularly inflected past tense forms, but not for irregulars [20,59]. One means of experimentally investigating morphological decomposition or affix stripping effects during the recognition of inflected words is via priming tasks in which the semantic, phonological and/or morphological relations between pairs of letter strings are manipulated. Priming effects (manifested, e.g., in shorter lexical decisions times) have been found in a small number of studies investigating the English past tense [e.g., Refs. [39,61]], but, as will become clear from the next section, their results are not fully conclusive.

The present study employed the event-related brain potentials (ERPs) as an online measure of brain activity during a morphological priming task with the aim of further examining possible decomposition effects. A brief introduction to relevant ERP results follows in a subsequent section.

1.1. Morphological priming of English past tense forms: results from previous studies

There is an extensive psycholinguistic literature on priming effects in lexical processing. Most research has been done on semantic, orthographical and phonological priming to investigate relationships among the meanings and the form properties of words in the mental lexicon [2,35]. With respect to English past tense formation, priming effects are received intensive investigation [15,16,29,38,39,42,47,61].

In their seminal paper, Stanners et al. [61] found that the lexical decision times to the second of a pair of identical words (e.g., *walk* followed by *walk*) was faster than to the first. Thus, repeating a word is presumed to facilitate access to its lexical entry. Surprisingly, Stanners et al. also observed an equivalent amount of facilitation when the first word was a regularly inflected past tense form (*walked*) and the second word its stem (*walk*). In other words, a word stem and its regularly inflected past tense form were equally effective primes for lexical decision on the stem. Irregular past tense forms on the other hand produced less priming of the stem than did the stem itself, e.g., *sing* was primed to a much lesser extent by *sang* than by *sing*. Stanners et al. [61] also found that derivationally suffixed words (e.g., *government*) were less effective primes than regularly inflected past tense forms. From these results the inference was made that regularly inflected forms are decomposed into stem and *-ed* whereas irregulars and derived forms are represented in the lexicon separately from their stems.

All subsequent experiments have confirmed Stanners et al.'s finding of full priming for regularly inflected words [16,29,39,42]. However, with respect to irregulars, the results are largely inconsistent. Where Stanners et al. had seen reduced facilitation for irregulars, Kempley and Morton [29] found no priming at all, whereas Fowler et al. [16] found full priming. Using a priming paradigm in which the prime immediately preceding the critical (target) word is masked, Forster et al. [15] also found full priming by irregular past tense forms. Moreover, Fowler et al. [16] report full priming by derived forms, a result which is also inconsistent with the partial priming found by Stanners et al. [61]. Marslen-Wilson et al. [39] investigated two subclasses of irregular past tense forms, (i) verbs such as *burnt–burn* and *felt–feel* with vowel changes and *-t* as the final consonant, and (ii) verbs such as *sang–sing*, *gave–give* with vowel changes only. They compared these irregular types with regular past tense forms in a cross-modal priming task. Only the regular past tense forms produced full priming. The past tense forms of semi-regular verbs (*burn–burnt, feel–felt*) yielded no priming, whereas those of pure vowel-change verbs such as *give–gave* actually led to an interference effect, with response times being significantly slower than following unrelated primes. The interference effect might be taken to reflect the presence of two lexical representations for *give* and *gave*, for example, which inhibit one another. Perhaps the strongest evidence to date for a regular–irregular dissociation in the English past tense system comes from a cross-modal priming study with English-speaking aphasics [38]: One subgroup of subjects exhibited (partial) priming effects for irregulars, but had lost (full) priming of regular verbs; another patient showed exactly the opposite pattern.

Taken together, priming data on the English past tense are inconclusive. It is true that in all studies regular past tense forms produced full priming, and this finding is compatible with dual-route models of morphological processing in which regular but not irregular past tense forms are said to be morphologically decomposed. Thus, the segmentation of *walked* into a stem (*walk*) plus affix (-ed) leads to activation of a lexical entry for the stem (*walk*) which serves as a prime for the target stem (*walk*) in the lexical decision task; hence the full priming for regulars. Alternatively, however, Rueckl et al. [47] argued that regular past tense forms are orthographically and phonologically more similar to their base forms than are irregular past tense forms; cf., for example, *walked* → *walk* vs. *taught* → *teach*, and it might be these different form properties that account for full priming of regular past tense forms. While the form properties of regulars and irregulars are clearly different for the examples quoted by Rueckl et al. [47], it is not generally the case that regulars are more similar to their base entries than irregulars. Many irregular past tense forms are in fact more similar to their base forms than the regulars, e.g., *hit*, *put* and other no-change verbs.

One approach for resolving this controversy between single and dual-mechanism models has been to investigate inflectional systems with more advantageous properties than the English past tense such as the German participle system [10]. While priming effects in German appear not to be attributable to different form properties of regular and irregular verbs, it does not necessarily follow that the same state of affairs holds for English.

1.2. ERP studies of repetition and morphological priming

As strictly behavioral methods have not (yet) been able to resolve the issues surrounding morphological priming in the English past tense system, it seems justified to search for complementary measures, such as event-related brain potentials (ERPs), that could yield additional information. ERPs have been used successfully to investigate language phenomena (for reviews, see Refs. [31,32,43]). Recently, a few ERP studies have addressed issues of morphological processing [21,45,67,68]. We will return to these in Section 4.

The design of the present study shares similarities with a widely used paradigm in the ERP literature-repetition priming. Many such studies have shown that when written words are repeated within a list, the ERP to their second presentation is associated with a widespread and long lasting late positive-going shift [4,5,24,28,41,44,48–51,60,70]. The ERP repetition effect is observed with pictures [52], faces [40], and orthographically legal non-words (e.g., ‘narg’, Refs. [54,55]) but not with orthographically illegal (‘dpltrsy’) non-words [55] or scrambled pictures [49].

Based on its differential sensitivity to various stimulus and experimental factors the ERP repetition effect is considered to comprise at least two distinct effects: an initial reduction of the N400 component between 200 and 500 ms followed by an enhancement of a late positive component (LPC) between 500 and 800 ms. The LPC enhancement is most evident with low frequency words [53,66]. We consider interpretations of the functional significance of these components in Section 4.

As with identical repetition, formal priming (e.g., *scan–scandal*) modulates N400 amplitudes. However, only experiments using a lag of zero between prime and target have been reported so far [13]. Thus the longevity of formal priming effects is unknown.

1.3. The present study

If regular forms are morphologically decomposed while irregulars are not, we expect regular and irregular past tense forms to give rise to different ERP priming patterns on their stem forms: specifically, we predict that as the decomposition of regular past tense forms results in direct access to their stems they should show a modulation of the N400 component to their stems similar to the repetition priming effect. On the other hand, if irregular complex forms have lexical entries separate from their stems, which cannot directly access by their stem forms, they should produce less modulation of the N400 component to their stems.

To investigate morphological priming in English, stem forms of regular and irregular English verbs were used as the critical stimuli. In the primed condition, these were preceded by their past tense forms (e.g., regular: *stretched–stretch*, irregular: *fought–fight*), while in the unprimed condition they were preceded by past tense forms of unrelated verbs (e.g., regular: *walked–stretch*, irregular: *sang–fight*). The difference between the ERPs to the primed and unprimed stems was taken as a measure of morphological priming.

Because of the properties of the English language, the two critical conditions in the present study had inevitably differences in the degree of formal (phonological and orthographic) similarity between prime and target stimuli. Steps were therefore taken to minimize the potential contribution of undesired formal priming. Firstly, the inter-item lag between the first and second word of a pair was between 5 and 9 items to reduce immediate formal priming effects. Secondly, letter strings were presented such that the second word of a pair was always in a different case than the first word to minimize perceptual priming. Also, we included a phonological control condition (see Ref. [13]), where each target word was preceded by a word that either did or did not share the initial phonemes (e.g., *sincere–sin* vs. *board–sin*). In addition, nonce verbs were constructed that followed either a regular or an irregular inflectional pattern.

2. Methods

2.1. Subjects

Nineteen healthy, young right-handed (one with a left-handed first degree relative) native speakers of English (14 women, 18 to 28 years of age, mean 20.3) gave informed consent to participate in a two session experiment. Subjects had normal or corrected-to-normal vision and were naive with regard to the experimental background.

2.2. Stimuli and procedure

The following stimuli were used to generate stimulus lists, with word frequencies based on the frequency dictionary of Francis and Kucera [17] (for a list of the stimuli, see Appendix A).

1. Regular English verbs ($n = 114$, mean frequency: 78 per Mio., mean length: 5 letters)
2. Irregular English verbs ($n = 114$, mean frequency: 79 per Mio., mean length: 5 letters)
3. pairs of English words that shared the first 3 to 6 letters ($n = 114$, e.g., board–boar, battery–batter)
4. pairs of nonce verbs in which the past tense forms were suffixed with -ed, following a regular inflection pattern ($n = 114$)
5. pairs of nonce verbs in which the past tense was formed in analogy to existing irregular verbs of English ($n = 114$). The analogy was rhyme, i.e., each nonce verb shared the final vowel and consonant(s) with an existing verb, e.g., *fraw–frew* based on *draw–drew*
6. 100 English words (fillers)
7. 252 non-words (fillers)

These stimuli were arranged in several lists containing 1112 stimuli each, 556 words and 556 non-words. Each list included 76 items (= *primes*) for each of the five stimulus categories (see 1–5 above), each followed after 5–9 items by another stimulus item (= target) that was either related or unrelated to the prime; 38 were related, 38 were unrelated. There were also 100 additional word stimuli (word fillers) and 252 additional nonce word stimuli (nonce fillers); the following table presents an example stimulus set:

Half of the stimuli appeared in upper-case letters, while the other half was shown in lower case letters. If the first stimulus of a pair had been shown in upper case, the second stimulus was shown in lower case and vice versa.

As each stimulus category (e.g., irregular verbs) comprised 114 items, all items were used in each list (for example: 38 irregular verbs for the primed irregular condition, and 76 irregular verbs for the unprimed irregular condition—38 in their past tense and 38 in their stem form). No item was repeated in the same form within a given list. Six different lists were constructed with all items rotated systematically through all conditions (past tense, stem, primed and unprimed pairs, upper and lower case). Each subject saw two of the lists (one in each of the two sessions).

Words were presented for 300 ms in an orange color against a dark background within a rectangle outlined in red. At the viewing distance of 100 cm, the words subtended 0.7 degrees of visual angle in height and between 1.7 and 4.0 degrees of visual angle in width. The interstimulus intervals were varied randomly between 1600 and 2200 ms (rectangular distribution).

The subjects were instructed to perform a lexical decision (word/non-word) for each stimulus and to indicate their response by pressing one of two buttons held in each of the left and right hands. The assignment of response type to the left and right hand was counterbalanced across sessions. The experiment (without breaks) lasted 35 min per session.

2.3. Recording and analysis

The EEG was recorded from 59 scalp tin electrodes arranged in a geodesic fashion in an elastic cap (Electro-Cap) with reference electrodes placed on the mastoid processes. Biosignals were recorded to the electrode on the left mastoid process and re-referenced off-line to the mean of the activity at the two mastoid processes. Additional electrodes were attached to the left and right external canthi and at the left and right lower orbital ridges to monitor horizontal and vertical eye movements for later off-line rejection. The biosignals were amplified with a bandpass from 0.01 to 100 Hz, digitized at 250 points per second and stored on magnetic disk. After artifact rejection by an automated procedure using individualized amplitude criteria on the eye-channels and the frontopolar channels plus additional routines to detect amplifier blocking and gross voltage shifts in the scalp channels, ERPs were averaged for 1024 epochs including a 100 ms prestimulus interval. The waveforms were quantified by mean-amplitude measures in time windows 250 to 400 ms and 500 to 800 ms. Visual inspection of the data revealed that the majority of the effects were seen in frontal, central and parietal areas. Therefore, the data from 22 lateral sites from these areas were entered in a repeated measures analysis of variance (ANOVA). The data from the other electrodes were used for visualization of the effects via isovoltage maps. The Huynh–Feldt correction for inhomogeneities of covariance was applied whenever applicable. Reported are the original degrees of freedom and the corrected p-values.

3. Results

3.1. Behavioral results

Lexical decision times for the stem forms and the second words of the phonological control condition are given in Table 1. Pseudo-words were responded to considerably more slowly than words ($F(1,18) = 140.59$, $p < 0.0001$). No main effects of priming were found either in the omnibus ANOVA ($F(1,18) = 0.21$, n.s.) or when each condition was tested independently.

The morphologically complex prime words (699.8 ± 91.1 ms) were responded to more slowly than the stems (662.1 ± 90.1, $F(1,18) = 124.56$, $p < 0.0001$, analysis restricted to the real verb stimuli and unprimed stem forms).

3.2. ERP effects for real verbs

ERPs to the primed and unprimed regular stems at four midline sites are shown in Fig. 1 (left column). Beginning at about 250 ms poststimulus and ending at about 450 ms at most sites the ERPs to the primed words are more positive than those to the unprimed target stems. This difference has a centroparietal distribution, and therefore likely represents a modulation of the N400 component. Over right frontotemporal sites there is also a later effect with the ERPs to primed stems taking a more positive course. These effects can also be seen in the isovoltage maps (Fig. 2) depicting the voltage differences between primed and unprimed stems. Between 250 and 400 ms a centroparietal difference emerges for the regulars, whose distribution corresponds closely to previous distributional data published for the N400 [11]. In striking contrast there is no modulation of the N400 component in the ERPs to the irregular target stems (Fig. 1, second column, Fig. 2). There is, however, a right preponderant centroparietal positivity beginning at about 450 ms.

Table 1
Reaction times (standard deviations) to the stems of the four verb conditions and the second words of the phonological priming condition

	Primed	Unprimed
Regular	653.7 ± 95.4	660.5 ± 87.5
Irregular	668.4 ± 95.9	665.7 ± 87.8
Nonce ‘regular’	744.2 ± 88.9	740.4 ± 84.7
Nonce ‘irregular’	739.2 ± 96.7	742.9 ± 101.9
Phonological	674.6 ± 88.2	675.1 ± 84.4

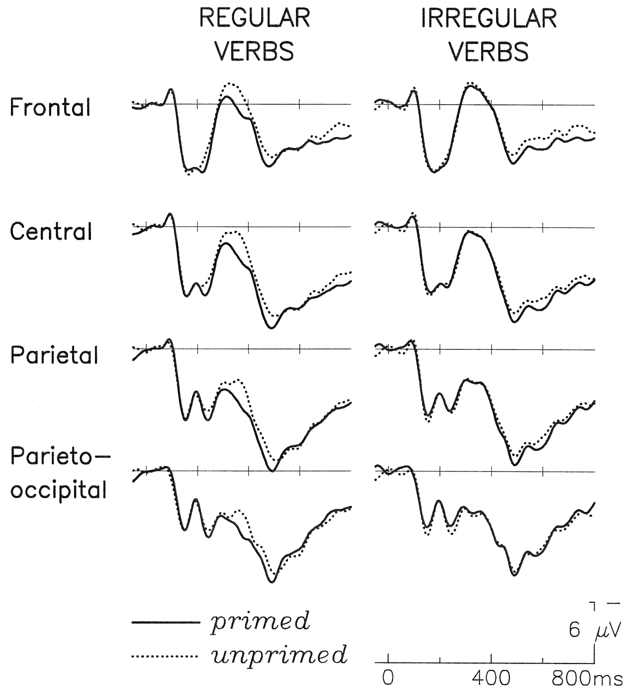

Fig. 1. ERPs from primed and unprimed stems of regular verbs are shown in the left column for four midline sites. Primed stems show a more positive waveform beginning at about 200 ms and lasting until about 500 ms. By contrast, the irregular verbs do not show a modulation in the 200–500 ms range but rather a later positivity is observed for the primed stems.

Statistically, a main effect of priming was found between 250 and 400 ms ($F(1,18) = 8.87$, $p < 0.01$); there was no effect of regularity ($F(1,18) = 1.06$, n.s.). The exclusive presence of a priming effect for regular verbs in this time window gave rise to a regularity by priming interaction ($F(1,18) = 5.45$, $p < 0.05$), which did not interact with electrodes.

Between 500 and 800 ms neither the main effect of priming ($F(1,18) = 2.94$, $p = 0.10$) nor the interaction between priming and regularity ($F(1,18) = 1.32$, n.s.) were significant. Thus, the late effect seen for irregular words proved to be unreliable for the 300 ms analysis epoch (but see Fig. 5 for additional statistical data on this effect).

3.3. ERP effects for nonce verbs

Fig. 3 (columns 1 and 2) shows the ERPs at three midline sites for the ‘regular’ and ‘irregular’ nonce verbs. ‘Regular’ nonce words were associated with a very small effect in the N400 range; beginning at about 450 ms the ERPs to primed nonce words were more positive over centroparietal regions than to unprimed nonce words. For ‘irregular’ nonce verbs primed and unprimed target stems did not show any major difference.

Statistically, neither the main effects of regularity ($F(1,18) = 0.95$, n.s.) and priming ($F(1,18) = 2.29$, n.s.) nor their interaction ($F(1,18) = 0.41$, n.s.) were significant

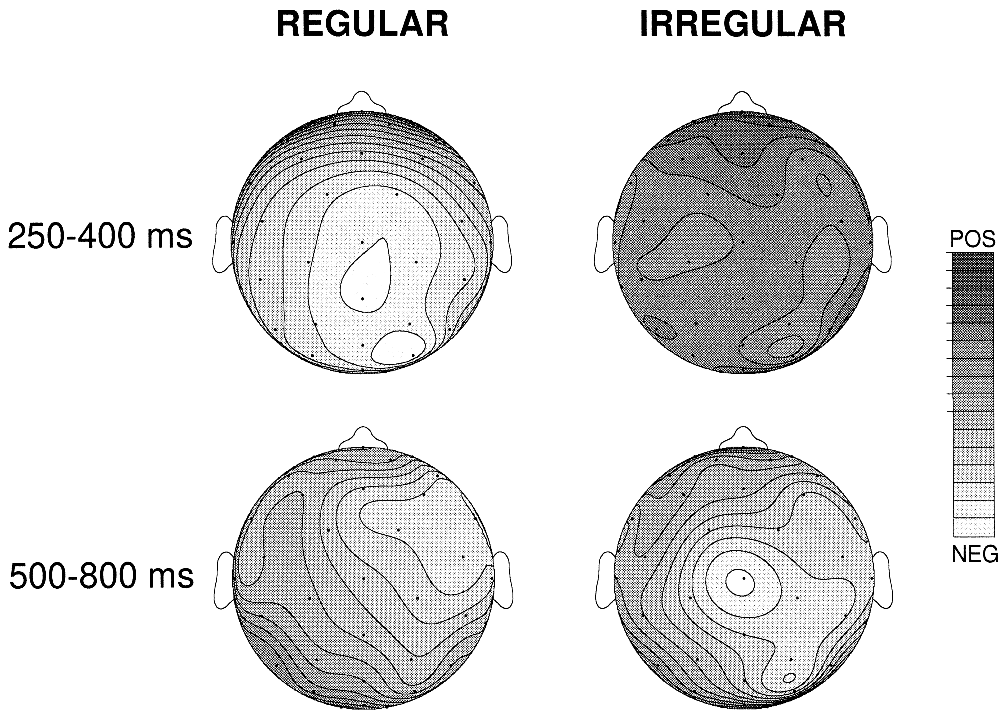

Fig. 2. Topographical distribution of the priming effect, i.e., the difference between primed and unprimed stems (isovoltage mapping with spherical spline interpolation). Between 250 and 400 ms the regular verbs show a centroparietal difference that is reminiscent of the typical distribution for the N400 component reported in the literature. No priming effect is observed for the irregular verbs in this time-window. Between 500 and 800 ms the irregular verbs show a right preponderant centroparietal priming effect, whereas the regular verbs are associated with a low amplitude right frontal effect.

between 250 and 400 ms. Between 500 and 800 ms the larger positivity for primed 'regular' target nonce verbs was significant (main effect of priming, $F(1,18) = 5.23$, $p < 0.05$; regularity by priming interaction ($F(1,18) = 4.87$, $p < 0.05$; no main effect of regularity, $F(1,18) = 1.42$).

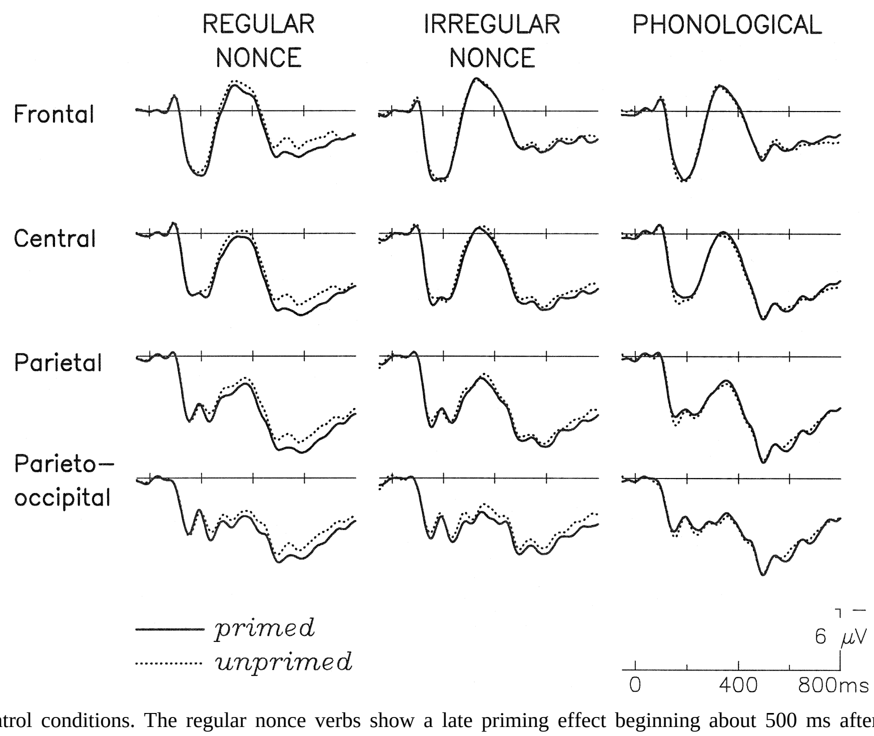

Fig. 3. Data from the control conditions. The regular nonce verbs show a late priming effect beginning about 500 ms after stimulus onset, while the irregular nonce verbs and the phonological controls do not display an ERP priming effect.

3.4. ERP effects for phonological controls

The ERP waveforms from the phonological control condition are shown in Fig. 3 (right column). Neither visual inspection nor quantitative analysis of these data revealed any reliable differences between primed and unprimed target words in this condition (250–400 ms, $F(1,18)=0.65$, n.s.; 500–800 ms, $F(1,18)=1.29$).

3.5. Comparison of priming effects

To compare the electrophysiological priming effects, difference waves (unprimed minus primed) were computed for the five different experimental conditions. These are shown in Fig. 4 for four midline sites. It is clear that priming in the regular verbs manifests itself in a negative difference with an onset at about 200 ms. Both the irregular verbs and the regular nonce verbs show a somewhat later and less prominent effect, albeit with a different anterior–posterior distribution, whereas for the irregular nonce verbs and the phonological control conditions there are no priming effects whatsoever.

To illustrate the timing differences of these priming effects, mean amplitude measures were taken in consecutive 50 ms intervals (25–75 ms, 75–125 ms, etc.) on the four midline electrodes and entered into separate ANOVAs. The F-values plotted against time are shown in Fig. 5. The priming effect for the regular verbs appears earlier than the priming effect in the irregular verbs and the regular nonce verbs.

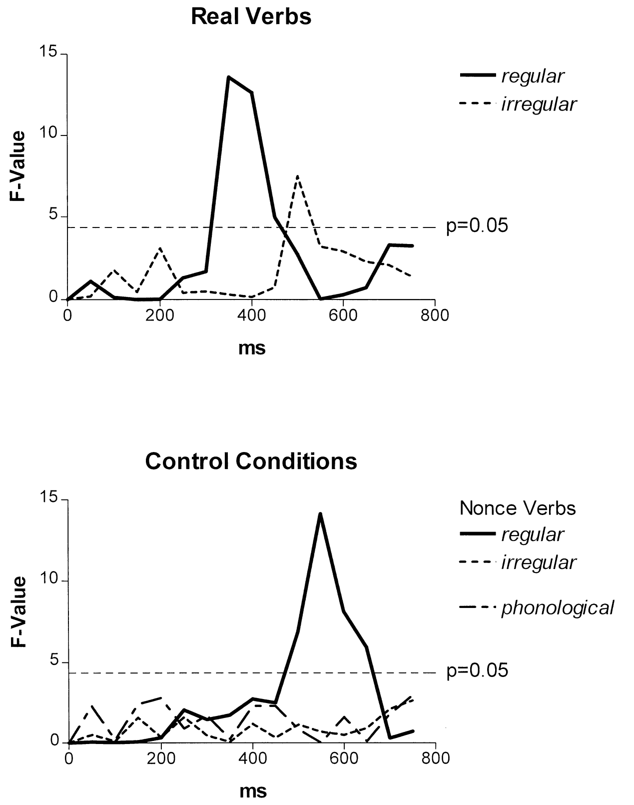

Fig. 5. F-values (Factor: primed vs. unprimed stimulus) are graphed against time. Mean amplitude measurements were taken in consecutive 50 ms time-windows centered on the time-points given in the figures (i.e., time-point 50 ms represents the time-window 25 to 75 ms) on the four midline electrodes illustrated in Fig. 4. The priming effect becomes highly significant for the regular verbs at 200 ms, whereas the priming effects in the irregular verbs and regular nonce verbs attain significance much later.

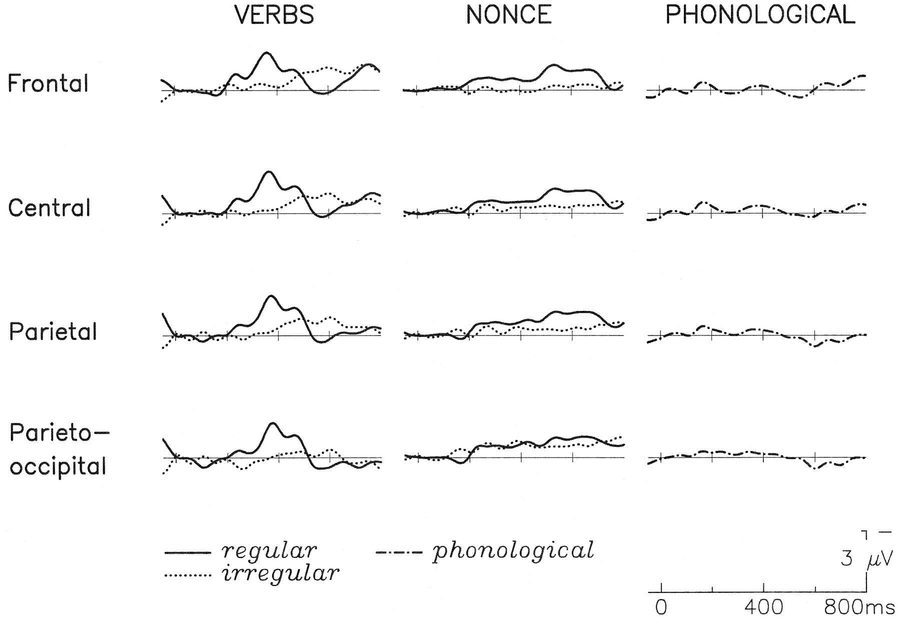

Fig. 4. Difference waves (primed–unprimed) for four midline electrode. These difference waves illustrate the electrophysiological effect of priming. Only the regular verbs are associated with a modulation in the N400 range, whereas for irregular verbs and regular nonce verbs a later effect is observed.

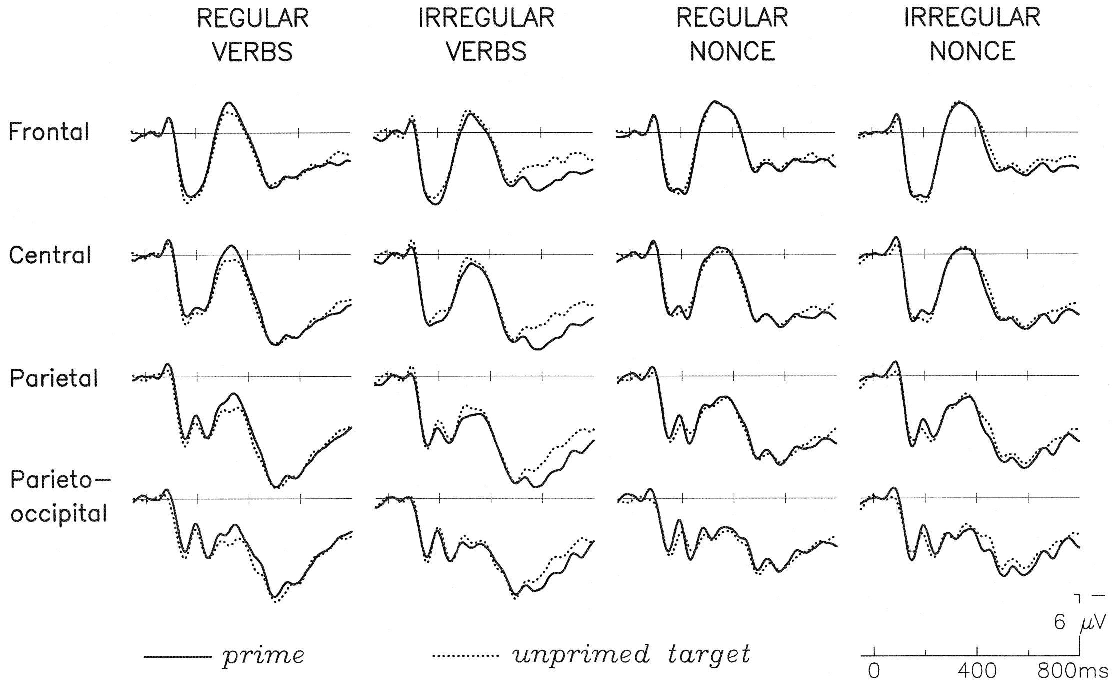

Fig. 6. Comparison of past tense (primes) and stem forms (unprimed targets). Only the stimuli from the unprimed pairs were used for this figure. The regular verbs show a small difference between the stem and past tense forms in the N400 range, which was not significant. By contrast, irregular past tense forms were characterized by a more positive waveform beginning at about 500 ms. No difference was seen in the two nonce verb conditions.

3.6. Morphologically complex forms vs. stems

Fig. 6 shows a comparison of the ERPs to the past tense forms and to the unprimed target stems at four midline sites. Only stimuli from the unprimed condition (i.e., *stretched... walk*) are included in order to avoid confounding the comparison between complex forms and stems with priming effects. Past tense and stem forms are virtually superimposable in the two nonce word conditions and statistical comparison reveals no reliable differences between them (all $F(1,18) < 1.5$, n.s.).

For the regular verbs the stem forms are slightly more positive between 250–500 ms, but this difference is not reliable (250–400 ms, $F(1,18) = 1.96$, n.s.; 500–800 ms, $F(1,18) = 0.01$, n.s.)

The irregular verbs, on the other hand, show a pronounced difference between past and stem forms with the former being more positive between 500–800 ms ($F(1,18) = 6.19$, $p < 0.025$; 250–400 ms, $F(1,18) = 0.95$, n.s.).

4. Discussion

With regard to the main comparison of the present study a clear dissociation of regular and irregular verbs in terms of their ERP morphological priming effects was found. Only the regular English verbs were associated with a modulation of the N400 component; the irregulars did not show such an effect. As regular and irregular verbs differ not only in their morphological make-up but also in the degree of phonological and orthographical overlap it seems important to consider the results from the current control conditions as well as data from other ERP priming studies before discussing the dissociation of regular and irregular verbs in terms of morphological processing models.

4.1. Results from the control conditions

The phonological control condition was introduced to check the extent to which differential overlap in phonology and orthography could be responsible for the differential effects for the regular and irregular verbs. Doyle et al. [13] found that formal similarities between stimuli can give rise to ERP effects reminiscent of repetition priming effects. We, however, found no electrophysiological priming effects for formally related targets. Several important methodological differences between the two studies might explain the absence of a formal priming effect in our data: Firstly, we employed a case change between the prime and the target stimulus. As it has never been shown that effects of formal priming are case insensitive, the question of the extent to which these effects rely on the similarity of the case of prime and target remains to be solved. Secondly, we used a longer lag of 5–9 compared to 0 in the paper of Doyle et al. ERP priming effects are typically smaller at longer lags. A further difference was that in Doyle et al. the prime stimulus was always physically shorter than the target stimulus (*scan–scandal*), whereas in our study the reverse was true; in other words the prime was longer than the target (*board–boar*). These decisions were based on our desire to make this condition as similar to the critical conditions as possible. We believe that these three methodological differences in concert could well eliminate the formal priming effect observed by Doyle et al. [13] and account for the data pattern we observed.

The use of the two nonce word conditions was similarly motivated by the need to assess the effect of surface similarity on ERP priming effects: care was taken to construct the stems and the past tense forms of the nonce word conditions in close analogy to real words. But like the phonological control condition, both nonce word conditions failed to modulate the ERP in the N400 time range. Note again that most of the work on repetition priming and formal priming with nonce words has used an inter-item lag of 0 (e.g., Refs. [13,55]). There is, however, one report that included a condition with a lag of 6 [54]. Experiment 1 of that study revealed that repetition of visually presented words gave rise to a significantly more positive waveform for the repeated words between 200 and 400 ms beginning around 264 ms at the medial central electrode according to serial *t*-tests. By contrast, repetition of non-words (Experiment 2) yielded only a later repetition effect between 400 and 600 ms with an onset latency around 444 ms. The word and non-word repetition effects also differed in their scalp distribution. Moreover, visual repetition of auditorily presented non-words led to an even later and more parietally-distributed ERP repetition effect. Note that Rugg and Nagy [55] changed neither case nor font from prime to target.

In the present investigation an effect of priming was observed only for the 'regular' nonce words. Its onset latency around 500 ms was considerably later than that for the real regular verbs. Moreover, these two effects had different scalp distributions, suggesting that different neuronal populations give rise to the priming effects for regular verbs and regular nonce verbs. In keeping with the literature on late positive effects in priming experiments, the later effect for the primed regular nonce words might reflect contact of the target stem form with an episodic memory trace formed by the priming 'past tense' form. By the same token, the absence of an appreciable ERP priming effect for irregular nonce words can be explained by the greater difference between the 'past tense' and 'stem' forms in this case thereby precluding subjects from making the connection between prime and target at the long lags used here. The pattern of effects is also consistent with an explanation in terms of morphological decomposition: a regular past tense form of a novel verb is decomposed into stem + affix, whereas irregular nonsense verbs are not. The decomposed stem thus serves to prime that stem when it appears as the target.

Taken together, the control conditions show that the differences in priming between regular and irregular verbs cannot be attributed to the greater phonological and orthographical overlap between past tense and stem forms for regular verbs. The use of a lag of 5–9 and the change of case between prime and target stimuli appears to have successfully eliminated formal priming effects.

4.2. Priming effects to regular and irregular verbs

With formal similarity ruled out as an explanation for the priming effects found in the present study, we can now turn to the effects observed for the regular and irregular verbs. Before we discuss the ERP priming effects we would like to address the fact that none of the experimental conditions of the current study, not even the regular verbs, yielded reaction time priming effects. We suggest that the lack of priming effects in terms of RTs results from design aspects of our study. Whereas in RT-based priming experiments the primes immediately precede the targets, we had a long inter-item lag of 5 to 9 stimuli, to avoid purely formal or perceptual priming effects. Another difference is that while in previous studies primes and targets were presented in the same letter format, in our study each prime–target pair differed in its letter format to reduce purely visual– perceptual priming. Finally, and probably most importantly, the proportion of related items in our materials is only 7%, much lower than in previous behavioral priming experiments on the English past tense. It is conceivable that these factors account for the absence of any priming effect in the RT data.

The ERP priming effect in the regular verbs had a centroparietal scalp maximum and an onset latency around 250 ms (see Figs. 1 and 2), reminiscent of N400 modulation. The amplitude of this priming effect is considerably smaller (2.5 μV) than the typical 4 μV seen in repetition priming studies (e.g., Refs. [41,55]). One reason for this smaller amplitude might be the small proportion of related pairs within the stimulus list. Whereas in typical repetition priming studies a third of the stimuli are repeated (cf. Refs. [19,53]) the proportion in the current study was much lower. Current theories of priming suppose an expectancy driven mechanism contributes to priming effects [3], especially when the proportion of prime/target pairs within a list is high. There is evidence that expectancy also influences N400 amplitude [9]. Another reason might be the rather long lag.

While no consensus has been reached as to the functional significance of the N400 component, its amplitude is generally found to be sensitive to semantic/lexical factors. Thus, it has been suggested that N400 amplitude might vary with ease of lexical access [25,26,66]. Others have linked N400 amplitude to postlexical integration processes [6,9,22,60]. On the latter account, a word is easier to integrate in context when it has recently been activated either by repetition or a prior semantically related word. In support of the postlexical integration view Chwilla et al. [9] observed larger semantic priming effects in a lexical decision task with a higher proportion of related pairs, and no N400 priming effect when these stimuli were processed only at a shallow physical level (discrimination between upper and lower case letters). The authors concluded that the 'N400 is modulated when semantic aspects of word stimuli enter into the episodic trace of wordlike stimulus events'.

By this account primed target stem forms of regular verbs would—by virtue of their overlap with the episodic memory trace formed by the corresponding prime—be easier to process, hence leading to an attenuated N400 component. The lack of an N400 effect for the irregular verbs on the other hand suggests that the memory trace that was formed by the prime did not activate the representation of the stem form to a degree sufficient to yield N400 reduction.

Weyerts et al. [67] likewise observed smaller and later morphologically priming effects for irregular verbs in German. In their study, morphologically complex forms served as targets and were primed at a long lag (lag 13) either by their corresponding infinitive or by themselves. For the regular condition, identity priming and repetition priming both led to large and extended ERP effects over both N400 and LPC regions. For the irregular condition, on the other hand, only the identity priming condition modulated the N400, while the morphological priming condition was associated with a small and late positivity. It would have been informative to include an identity priming condition in the current study as well. However, given the scarcity of irregular verbs in English this would have required an undue lengthening of the experiment by two additional sessions.

4.3. ERPs and morphological processing models

The present study demonstrates regular–irregular processing differences in the English past tense system. We found a modulation of the N400 component for verb stems primed by regular past tense forms, but not for verb stems primed by irregular past tense forms. Control conditions showed that this priming effect is unlikely to have been caused by form–property differences between regular and irregular past tense verbs.

The ERP differences we found between regular and irregular past tense formation have implications for theoretical models of the mental lexicon. Unitary accounts of morphological processing in which no distinction is made between regular and irregular inflection provide only partial explanations for our findings. If all inflected words were stored in associative memory, as assumed in full-listing models of morphological processing, we would expect to find similar ERP priming effects for regular and irregular past tense forms. Our results show that this is not the case.

In connectionist accounts of morphological processing, priming effects of past tense forms are claimed to vary in strength depending on the degree to which prime–target pairs are formally similar [47]. Regular and irregular past tense forms in English do indeed differ in this respect, but the results from the control conditions used in our experiment indicate that the priming difference between regulars and irregulars is probably not due to differences in phonological and/or orthographic overlap.

According to the full decomposition model, one might assume that all inflected words are rule-based and that by applying the rules, past tense forms can access their corresponding stem forms. For example, the past tense form *sang* may be derived from the stem form *sing* through a morphologically conditioned rule that changes the vowel [i] to [æ]. If morphologically complex words were fully decomposed, we would expect this rule of 'lowering ablaut' [23] to be applied to *sang*, and in this way the stem *sing* should become accessible. Regular and irregular past tense forms should therefore access their stems equally well. This, however, is not the case as shown by the lack of an ERP priming effect for irregulars. Thus, while regular past tense forms appear to access their stems, the decomposition of irregulars seems to be futile. We conclude that the differences found between regular and irregular past tense formation do not seem to receive a satisfactory explanation from single-mechanism accounts of inflection.

According to dual-route models of morphological processing, regular past tense inflection is based on affixation of -ed to a stem to form inflected words such as *walk-ed*. Irregular past tense forms, on the other hand, are based on a look-up of inflected forms stored in the lexicon. In linguistic terms, regular verbs in English have one lexical entry, e.g., *walk*, and past tense forms are derived by affixation, whereas irregular verbs have subentries for past tense forms which are linked to the base entry [27,69]; an irregular verb such as *drive*, for example, is said to have two subentries, one for the past tense form *drove* and one for the participle form *driven*, in addition to the base entry *drive*. Our ERP results appear to support a distinction between lexically-based and affixation-based inflection. Regular past tense forms are decomposed into stem + affix, and in this way can directly access their corresponding base forms; the ERPs for regular past forms used as primes showed a reduced N400 on the target, a reflection of facilitated access to the base entry. There was no such effect for irregular past tense forms. In our terms, irregular past tense forms are stored as subentries in the lexicon, and can only indirectly activate their corresponding base entries from there. Hence, accessing a subnode of a lexical entry may yield some co-activation of the base entry, but it was not strong enough to produce an observable N400 modulation.

5. Conclusion

In addition to previous results on German and Italian inflection [21,45,67,68], the present findings on English constitute another case in which ERPs have been shown to capture the processing differences between the regular and irregular verbs. This pattern of differences is most consistent with the view that under the present circumstances regular complex forms are decomposed into stem and affix, whereas irregular past tense are not and hence do not serve as such effective primes.

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Appendix A

Regular verbs: use, unite, move, require, add, follow, reach, obtain, establish, close, limit, remain, force, end, talk, touch, paint, dedicate, fade, scream, rest, link, fold, kiss, smash, cook, dash, hunt, blink, blush, clench, drill, gasp, shield, deign, faint, flout, glide, call, ask, started, need, receive, walk, pass, report, serve, live, return, cover, play, raise, name, pick, wait, sign, print, washed, stretch, release, load, twist, pursue, carve, administer, crash, slump, choke, erupt, attest, blend, sort, boost, mend, chase, flirt, look, seem, turn, want, consider, happen, show, open, work, base, fill, cause, fix, state, mark, remember, collect, appoint, miss, smoke, press, stain, rush, vote, straighten, melt, drift, grunt, search, toss, bake, blame, dine, cough, dispute, moan, boom, blunt.

Irregular verbs: come, find, hold, bring, become, hear, stand, cling, break, win, grow, hang, bind, choose, sweep, eat, light, dig, tear, speak, fling, swear, kneel, undertake, overhear, swim, uphold, freeze, lend, shine, string, strive, mislead, sling, partake, shrink, overshoot, undo, got, took, fled, gave, kept, wrote, lost, built, meant, caught, wore, drew, drove, swung, sold, fought, threw, rode, bent, sang, flew, arose, forgot, foresaw, woke, sprang, blew, crept, spat, withheld, hid, bled, beheld, overcame, dwelt, forbore, mistook, sank, think, tell, know, begin, sit, send, run, lead, meet, spend, fall, strike, understand, shake, buy, drink, teach, feed, sleep, slide, stick, deal, ring, seek, steal, stride, awake, speed, weep, withdraw, weave, withstand, overtake, forgive, shoe, sting, befall, cleave.

Regular nonce verbs: luse, renite, zove, renire, chadd, brollow, fleach, protain, perclash, plose, zimit, bemain, lorce, jend, malk, youch, maint, denilate, hade, cheam, prast, nink, yold, fiss, dresh, mook, gash, dunt, hink, glesh, rentch, zill, masp, mield, heign, zain, mout, tride, shrall, fesk, lart, jeed, bequire, lalk, gass, renert, cherve, plive, remirn, wover, bley, faise, pame, gick, quait, drign, brind, zesh, bretch, retweaze, cload, brist, pertway, garve, adbrend, blosh, blump, twoke, elapt, betest, klend, dort, doost, rond, dase, lirt, yook, leem, furn, lont, condrender, goppen, trowne, bleapen, merk, zave, dwill, frause, drick, flade, fark, refrond, conjold, apprelch, brense, troke, shess, nain, drosh, hote, jaighten, quelt, zwift, drunt, weach, choss, grake, glame, rine, jough, displouse, broan, troom, prunt.

Irregular nonce verbs: wome–wame, jind–jound, zold–zeld, shling–shlought, beclome–beclame, mear–meard, trand–trood, dwing–dwung, queak–quoke, trin–tron, wrow–wrew, nang–nung, glind–glound, floose–flose, treep–trept, gleat–glate, pright–prit, nig–nug, brear–brore, fleak–floke, twing–twung, shnear–shnore, breel–brelt, overchake–overchook, undergrear–undergreard, klim–klum, upbrold–upbreld, greeze–groze, plend–plent, frine–frone, chring–chrung, blive–blove, misfread–misfred, tling–tlung, perfake–perfook, thrind–thrund, overbroot–overbrot, unclo–unclid, flet–flot, frake–frook, shlee–shled, bive–bave, dreep–drept, snite–snote, ploose–plose, tuild–tuilt, frean–reant, fatch–faught, nemear–nemore, fraw–frew, frive–frove, appring–apprung, chell–chold, gight–gought, bedrow–bedrew, zide–zode, betend–betent, gring–grung, indow–indew, forbret–forbrot, forebree–forebraw, nake–noke, ning–nang, zow–zew, freep–frept, prit–prat, onzold–onzeld, jide–jid, wreed–wred, appmold–appmeld, onbrome–onbrame, attrell–attreld, fordnear–fordnore, misglake–misglook, intring–intrang, shink–shought, zwell–zwold, swow–swew, forblin–forblun, dwit–dwat, thrend–thrent, misbrun–misbran, klead–kled, queet–quet, yend–yent, crall–crell, plike–ploke, underpland–underplood, glake–glook, huy–hought, afflink–afflank, kleach–klaught, cheed–ched, neep–nept, swide–swid, swick–swuck, termeal–termelt, onbling–onblang, treek–trought, sweal–swelt, blide–blode, anake–anoke, tneed–tned, preep–prept, withnaw–withnew, neave–nove, withdrand–withdrood, overplake–overplook, forblive–forblave, bloe–blod, tring–trung, bethall–bethell, threave–thrave.

Phonological condition: number–numb, every–ever, feet–fee, early–earl, caper–cape, market–mark, quince–quin, pattern–patter, king–kin, youth–you, master–mast, warm–war, yellow–yell, dollar–doll, beef–bee, blanket–blank, card–car, herd–her, pastor–past, ridge–rid, match–mat, bark–bar, hitch–hit, rocket–rock, willow–will, fancy–fan, carpet–carp, patch–pat, center–cent, gully–gull, dense–den, wander–wand, needle–need, trumpet–trump, beaker–beak, rump–rum, blazer–blaze, limpid–limp, since–sin, several–sever, matter–matt, board–boar, peace–pea, army–arm, farm–far, charge–char, bank–ban, camp–cam, fund–fun, fellow–fell, inner–inn, start–star, screen–scree, panel–pan, lesson–less, belly–bell, tent–ten, battery–batter, damp–dam, wedge–wed, bitch–bit, weird–weir, seam–sea, shrewd–shrew, tart–tar, bust–bus, pansy–pan, twinge–twin, manor–man, hatch–hat, lapse–lap, booty–boot, twitch–twit, pawn–paw, torch–tor, divest–dive, against–again, form–for, week–wee, party–part, county–count, season–seas, corner–corn, style–sty, sight–sigh, factor–fact, dogma–dog, hence–hen, wagon–wag, firm–fir, whisky–whisk, fence–fen, butter–butt, pitch–pit, tooth–too, paint–pain, lawn–law, silly–sill, locust–locus, shovel–shove, topic–top, howl–how, vowel–vow, tackle–tack, ramp–ram, easel–ease, scant–scan, plant–plan, scarf–scar, rustic–rust, wanton–want, offer–off, trickle–trick, ketchup–ketch.

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