Graded Effects of Regularity in Language Revealed by N400 Indices of Morphological Priming

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Abstract

■ Differential electrophysiological effects for regular and irregular linguistic forms have been used to support the theory that grammatical rules are encoded using a dedicated cognitive mechanism. The alternative hypothesis is that language systematicities are encoded probabilistically in a way that does not categorically distinguish rule-like and irregular forms. In the present study, this matter was investigated more closely by focusing specifically on whether the regular–irregular distinction in English past tenses is categorical or graded. We compared the ERP priming effects of regulars (*baked–bake*), vowel-change irregulars (*sang–sing*), and "suffixed" irregulars that display a partial regularity (suffixed irregular verbs, e.g., *slept–sleep*), as well as forms that are related strictly along formal or semantic dimensions. Participants performed a visual lexical decision task with either visual (Experiment 1) or auditory prime (Experiment 2). Stronger N400 priming effects were observed for regular than vowel-change irregular verbs, whereas suffixed irregulars tended to group with regular verbs. Subsequent analyses decomposed early versus late-going N400 priming, and suggested that differences among forms can be attributed to the orthographic similarity of prime and target. Effects of morphological relatedness were observed in the later-going time period, however, we failed to observe true regular–irregular dissociations in either experiment. The results indicate that morphological effects emerge from the interaction of orthographic, phonological, and semantic overlap between words. ■

INTRODUCTION

A key aspect of human language is the use of highly regular patterns to mark grammatical relationships. Grammatical morphology provides many examples of this: Languages can productively combine elements of meaning (morphemes) through a variety of mechanisms including concatenation (prefixing, suffixing, and infixing). Perhaps the most closely studied example is past tense in English, which marks most verbs using a variant of the "–ed" ending (e.g., *baked*, *robbed*, *tested*). Its productive nature has led to the suggestion that a generative rule is used to concatenate the –ed suffix to verb roots (Pinker, 1998; Marcus, Brinkmann, Clahsen, Wiese, & Pinker, 1995). Likewise, morphologically complex forms are assumed to be recognized using a decomposition process that breaks them into their constituent morphemes (e.g., *baked* is recognized as *bake* and *–ed*; Clahsen, 1999; Pinker, 1991; Prince & Pinker, 1988).

One complication to this account is the presence of irregular forms that do not adhere to the regular default pattern. For instance, about 5% of all English verbs and 14% out of 1000 most frequent verbs are irregular (Marcus et al., 1995); that is, they are marked in other ways, including changing a vowel or consonant (*take–took*, *sit–sat*, *make–made*), changing the vowel and adding a final consonant (*sleep–slept*, *think–thought*), no change at all (*hit–hit*), or completely changing the verb altogether (*go–went*, *be–was*). Although some formal accounts have suggested ways that additional rules might be used to account for these forms (Albright & Hayes, 2003; Halle & Mohanan, 1985), one popular theory suggests instead that irregular forms are, in fact, processed using a qualitatively separate mechanism from regulars (Ullman, 2004; Clahsen, 1999; Sonnenstuhl, Eisenbeiss, & Clahsen, 1999; Pinker, 1991, 1998; Marcus et al., 1995). This "dual-mechanism" theory holds that irregular past tense forms are instead stored in an associative memory system alongside other lexical items (including regular stems such as *bake*).

Representation of morphologically complex words has traditionally been investigated using reaction time (RT) measures in behavioral tasks. Of particular interest are studies of morphological priming, which have shown faster recognition of a word such as *bake* following presentation of a morphologically related prime such as *baked* (Feldman, 2000; Frost, Deutsch, Gilboa, Tennenbaum, & Marslen-Wilson, 2000; Rastle, Davis, Marslen-Wilson, & Tyler, 2000; Drews & Zwitserlood, 1995; Marslen-Wilson, Hare, & Older, 1993; Grainger, Cole, & Segui, 1991; Bentin & Feldman, 1990; Stanners, Neiser, Hernon, & Hall, 1979). Such data might suggest that listeners maintain a shared underlying representation of the prime and the target, and that recognizing a complex form involves decomposing it into its root and affixes. The results for irregulars are less consistent. Some studies have found weaker or no priming effects for

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irregular forms (Sonnenstuhl et al., 1999; Marslen-Wilson et al., 1993; Kempley & Morton, 1982; Stanners et al., 1979), whereas others found facilitation for irregulars that was larger or equivalent to that of regular forms (Longworth, Marslen-Wilson, Randall, & Tyler, 2005; Tyler et al., 2002; Fowler, Napps, & Feldman, 1985). Although the dual-route theory can accommodate priming for both types of forms, it predicts differences in processing of regular and irregular verbs. Previous ERP studies have indeed found priming differences between regulars and irregulars, and these dissociations were often interpreted in support of the dual-mechanism theory. However, recent findings indicate that regular–irregular differences might be due to the formal rather than grammatical differences in the prime–target relationship (Justus, Larsen, de Mornay Davies, & Swick, 2008).

Not all psycholinguistic theories rely on the concept of rules and exceptions to explain morphology. In particular, the connectionist perspective (McClelland & Patterson, 2002; Plaut & Gonnerman, 2000; Joanisse & Seidenberg, 1999; Rumelhart & McClelland, 1986) proposes that morphology is encoded as statistical regularities that capture systematic relationships among forms. On this view, a single type of computational mechanism is used to process all morphologically complex words. Differences in how regular and irregular forms are processed stem from the extent to which processing can rely on phonological, orthographic, and semantic overlap among related forms. With respect to past tense, regular forms are phonologically and orthographically more similar to their present tense forms, leading to a greater reliance on these sources of information for producing and recognizing them. In contrast, irregulars are less similar to their stem forms. As a result, the system relies more heavily on semantic information for recognizing these forms (Joanisse & Seidenberg, 1999). Recent analyses of lexical statistics further indicate that irregulars have more semantic neighbors that are irregular and tend to cluster more densely in semantic space than regular verbs do (Baayen & Moscoso del Prado Martin, 2005), again indicating that semantic mechanisms play a stronger role for irregular inflections.

Consistent with this view, a number of studies have suggested that morphological priming effects can, in fact, be influenced by semantic, phonological, or orthographic factors (Pastizzo & Feldman, 2002a; Marslen-Wilson et al., 1993; Napps, 1989; Forster, Davis, Schoknecht, & Carter, 1987; Kempley & Morton, 1982; Stanners et al., 1979). Building on these results, it has been found that the strength of morphological priming effects can be modulated by orthophonological similarity (Kielar, Joanisse, & Hare, 2008; Basnight-Brown, Chen, Hua, Kostic, & Feldman, 2007; Pastizzo & Feldman, 2002a, 2002b) and semantic relatedness (Gonnerman, Seidenberg, & Andersen, 2007; Feldman, Soltano, Pastizzo, & Francis, 2004; Feldman & Soltano, 1999). Just as importantly, these effects are not all-or-none. Instead, priming can occur for both regular and irregular forms, depending on task parameters. For example, the processing time of the prime affects target recognition by modulating the influence of formal and semantic factors. Effects of formal overlap tend to decrease as the processing time of prime increases, whereas semantic similarity effects increase with processing time (Kielar et al., 2008; Feldman et al., 2004; Dominguez, Segui, & Cuetos, 2002; Feldman, 2000; Rastle et al., 2000; Feldman & Soltano, 1999). Similarly, presentation modality appears to influence the effect of regularity on priming (Kielar et al., 2008; Feldman et al., 2004; Feldman & Prostko, 2002; Pastizzo & Feldman, 2002b). For instance, whereas priming effects under visual presentation, especially at short SOAs, tend to be influenced by the orthographic similarity of primes and targets, auditory presentation is more sensitive to the semantic and phonological aspects of words. Stated generally, morphological effects in lexical decision tasks vary with SOA and presentation modality and the degree to which these task parameters allow for the interaction between form and meaning dimensions of similarity.

ERP Indices of Morphological Processing

On the whole, then, it remains unclear whether dissociations in priming of regular and irregular forms can be better accounted by their morphological regularity or by the differential reliance on form and meaning information used in their computation. One potential source of information in this regard might come from ERPs, which have increasingly been used to more closely investigate morphological processing and representation. This may provide a more complete picture by showing how word recognition processes unfold in real time. That is, although behavioral measures such as RT represent the end point of multiple language processing stages, ERPs allow us to dissect the time course of word recognition in a way that might isolate processes uniquely related to morphology, rather than orthography, phonology, and semantics.

A primary focus in this respect has been the N400 ERP component, and in particular, priming-related reductions in N400 amplitude. For instance, N400 repetition priming is found when a word is repeated within a list, compared to its first presentation (Hamberger & Friedman, 1992; Bentin & Peled, 1990; Holcomb & Neville, 1990; Smith, Stapleton, & Halgren, 1986; Rugg, 1985). Similar effects are also observed when a word is preceded by a semantically or morphologically related word, compared to when it is preceded by an unrelated word (Münte, Say, Clahsen, Schiltz, & Kutas, 1999; Bentin, McCarthy, & Wood, 1985). The N400 is thought to be sensitive to the lexical–semantic aspects of language processing (Kutas & Federmeier, 2000; Kutas & Hillyard, 1980), and in particular, the ease of accessing the word in memory (Van Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991; Holcomb & Neville, 1990; Rugg, 1985). Although some results indicate that it is sensitive to unconscious, automatic meaning access (Deacon, Hewitt, Yang, & Nagata, 2000; Luck, Vogel, & Shapiro, 1996), it has also been linked to a postlexical integration process as well (Brown, Hagoort, & Chwilla, 2000; Brown & Hagoort, 1993; Holcomb, 1988, 1993). On this account, N400 priming occurs because the word is more easily integrated into an ongoing context, thanks to having been recently activated. If morphologically complex words are decomposed into stems and affixes during recognition, this should facilitate subsequent processing of the stem. This would suggest that priming a stem (*bake*) with a morphologically related word (*baked*) should lead to an attenuated N400, as both the stem and inflected forms are proposed to share a single lexical entry (Clahsen, 1999). By the same token, irregular words are not assumed to be decomposed, and thus, should produce either smaller N400 priming, or none at all.

There is some evidence to support this. Münte et al. (1999) used a delayed priming paradigm in which participants performed lexical decision on targets separated from primes by five to nine intervening items. The study found attenuated N400s for regular past tenses following a previously presented present tense form, but no similar effect for irregulars. Similar effects have also been found using other types of priming paradigms in German and Spanish (Rodriguez-Fornells, Münte, & Clahsen, 2002; Weyerts, Münte, Smid, & Heinze, 1996), again marked by stronger N400 priming effects for regulars than irregulars.

Other studies have used ERP measures of morphological violations to examine this same issue. In this paradigm, ERP responses to correctly formed complex words are compared to responses to words that have an incorrect suffix (e.g., German plurals: **muskel-s* instead of the correct *muskel-n*; German past tense: **gelauf-t* instead of the correct *gelauf-en*; **bringed* instead of the correct *brought*; **book* instead of correct *baked*; Penke et al., 1997; Weyerts, Penke, Dohrn, Clahsen, & Münte, 1997). Results of these studies showed that the amplitude and scalp distribution of ERP responses were different for incorrectly inflected regular versus irregular forms. In particular, applying a regular suffix to irregular items was associated with a left anterior negativity (LAN), whereas incorrectly inflected regulars elicited an N400 but no LAN. Similar differences have also been reported in English (Newman, Ullman, Pancheva, Waligura, & Neville, 2007; Morris & Holcomb, 2005), Italian (Gross, Say, Kleingers, Clahsen, & Münte, 1998), Catalan (Rodriguez-Fornells, Clahsen, Lleo, Zaake, & Münte, 2001), and Turkish (Münte, Anvari, Matzke, & Johannes, 1995).

Differences in ERPs to regulars and irregulars have typically been interpreted as supporting a dual-mechanism view. Note that such data may also be compatible with the alternative explanation, however, that these dissociations reflect differences in the representational characteristics of regulars and irregulars such as form and meaning. In the present study, we suggest a stronger test, which involves examining whether the regular–irregular distinction is fully bipartite, or is, in fact, a graded one as predicted by the connectionist theory (Kielar et al., 2008; Joanisse & Seidenberg, 2005). To test this, we compare priming for regulars along with two sets of irregular verbs. The first are "suffixed irregular" verbs such as *kept*, *wept*, and *slept*. Linguists have referred to these forms as semi-weak, as they more closely resemble regulars in terms of their similarity to regular verbs, and their partial consistency. They are formally irregular because they do involve a somewhat unpredictable change to the stem; however, they also involve adding a regular-like suffix. The results of previous studies indicate that the brain responses for these verbs are more similar to regular than vowel-change irregular verbs (Justus et al., 2008; Joanisse & Seidenberg, 2005). These forms are contrasted with "vowel-change" irregulars such as *take–took*, which do not take a regular-like ending, and are highly inconsistent.

We previously investigated the distinction between regulars and two types of irregular verbs on lexical decision RTs, using cross-modal and visual priming (Kielar et al., 2008). The results revealed a similar pattern of results for regulars and suffixed irregulars, reflecting the degree of form overlap between primes and targets, compared to vowel-change irregulars that tended to yield weaker priming effects. Moreover, the exact pattern of effects varied depending on task dimensions that modulated sensitivity to orthographic and phonological similarity (i.e., prime modality, prime–target SOA). The results suggested that the differences among forms can be attributed to the orthographic similarity of prime and target. Similarly, Justus et al. (2008) found similar N400 priming effects for regulars and weak irregulars using auditory lexical decision and auditory primes. That said, the strongest priming was found for strong irregulars, compared to regulars and weak irregulars, which is the opposite of what we might have predicted given prior findings in visual lexical decision. The direction of this effect might be attributed to the sensitivity of the auditory immediate priming task to the semantic relationship between words.

In summary, the present study examines whether regularity effects in visual recognition of past tenses are categorical or graded. Evidence for continuity in how these different verb types are processed would suggest that morphological priming occurs not because of decomposition, per se, but is instead due to differences in the basic types of representations that are used in processing of these forms. Importantly, the study did not merely look for the differences between regulars and irregulars, but rather sought to understand the underlying reasons for these dissociations.

EXPERIMENT 1: ERP VISUAL PRIMING

In this experiment, participants' ERPs were recorded as they performed a visual–visual priming task with lexical decision. Because visual priming has been used extensively to study morphological representation in RT studies, the study provided important continuity with this previous body of work. Further, employing visual modality allowed us to test the contribution of orthographic factors to morphological priming. Priming effects for morphologically related items were contrasted with the effects of shared meaning (*couch–sofa*) or form (*panel–pan*), to assess the extent to which such factors can explain observed ERP priming effects for morphological relatedness. A third control condition consisted of word pairs that overlapped with respect to both phonology and semantics (e.g., *screech–scream*, *sneeze–snort*); these items are termed the −M + P + S condition, following Gonnerman et al. (2007) and Rastle et al. (2000), and allowed us to examine whether ERP priming effects observed for past tense forms might occur due to the *interaction* of formal and semantic overlap, beyond what is observed for phonology or semantics alone.

Methods

Participants

Fourteen right-handed, native speakers of English gave informed consent to participate in this study. All procedures were approved by the University of Western Ontario Non-Medical Research Ethics Board Involving Human Subjects and the University of Western Ontario Department of Psychology Research Ethics Board. Participants were students at The University of Western Ontario, ages 17–33 years (M = 24, SD = 4), had normal (or corrected-to-normal) vision, and no history of neurological or psychiatric illness (age range = 17–33 years, M = 24, SD = 4) and received 2 hours of course credit or $20 for participating.

Materials

There were five sets of prime–target pairs (Table 1; Appendix A). In the first three, a past tense primed a corresponding present tense probe: 35 regularly inflected prime–target pairs (*baked* priming *BAKE*), 36 vowel-change irregulars followed by their stems (*took–TAKE*), and 24 suffixed irregular prime–target pairs (*slept–SLEEP*). The orthographic/phonological items consisted of 34 pairs related in form only (*fairy–FAIR*); the semantic items were consisted 34 semantically related word pairs (*cherry–GRAPE*). Finally, the −M + P + S condition consisted of 27 morphologically unrelated but semantically and phonologically related prime–target pairs (*scratch–SCRAPE*).

Targets were equated as closely as possible across conditions for natural log frequency (CELEX; Baayen, Piepenbrock, & Gulikers, 1995), length (number of letters), and orthographic neighborhood (Coltheart's N; Coltheart, Davelaar, Jonasson, & Besner, 1977). As expected, conditions did vary with respect to degree of orthographic overlap between prime and target (defined as the number of letters shared in the same position between prime and target, divided by the number of letters in the longer word; Pastizzo & Feldman, 2002a). This is an important characteristic of regular versus irregular past tense verbs and represents a key manipulation in this study. Note, however, that exact matching on length was not possible for the ortho/phonological targets between conditions without compromising the frequency match. Similarly, frequency and length matching for the −M + P + S condition with other conditions was not possible because most of these words were from low-frequency neighborhoods.

Finally, 338 filler pairs were constructed by pairing words not included in the above conditions with either an unrelated real word or a nonword target (e.g., *want*–FOLD; *collect*–LORCE). The unrelated word fillers included a combination of noun–noun (e.g., *metal*–POTATO), noun–adjective (e.g., *brain*–NICE), noun–verb (e.g., *pocket*–COOK), and verb–verb trials (e.g., *sort*–TWIST). The nonword filler condition was included to provide "no" response trials in the lexical decision task. It consisted of orthographically legal and pronounceable nonword targets created by changing one or two letters of a familiar English word (e.g., HUBE, SMOP).

Priming effects were calculated by comparing each prime condition to an equal-sized set of unrelated word pairs. These were created by pairing the target words in each condition with a prime from another pair in the same condition (e.g., *chewed*–BLINK; *sang*–WRITE; *wept*–FEEL). There were six different unprimed lists, a separate one for each word condition, such that each primed list had its own unrelated list to accompany it.

Two lists of prime–target pairs were constructed, which differed as to whether a related prime preceded a given target. All primes were used in each list such that half of the word targets were paired with the related prime (List A: *rented–rent*, *walked–walk*; List B: *reached–reach*, *frowned–frown*) and half with an unrelated prime (List A: *reached–frown*, *frowned–reach*; List B: *rented–walk*, *walked–rent*). This allowed us to present each target with either a related or unrelated prime. Due to the large number of items required in the ERP paradigm, each participant was tested on both lists. However, the presentation order was counterbalanced such that half the time a target was first presented with a related prime, and with order counterbalanced across participants. Although the presentation of an item more than once in an experiment can underestimate behavioral and ERP priming effects, we note that this affected all conditions equally and, therefore, did not favor any of the competing hypotheses considered here. It also provided us with an appropriate number of trials for each condition, an important concern given that English provides relatively few irregular past tenses to choose from with respect to the factors of interest in our study. The strategic factors were minimized by the fact that targets were preceded by their inflected form in a small subject of trials (12% of all prime–target pairs).

Procedure

Primes and targets were presented visually. On each trial a fixation cross appeared in the center of the screen for 250 msec. Following a 150-msec delay, a lowercase visual prime was presented for 200 msec, immediately followed by a 100-msec pattern mask (XXXXXXXXXX). The target

Table 1. Stimulus Characteristics of the Word Items in Past Tense ERP Experiments

	Morphologically Related					
	Regulars (Baked–Bake)		*Suffixed Irreg (Kept–Keep)*		*Vowel-change (Sang–Sing)*	
	M	*SD*	*M*	*SD*	*M*	*SD*
Length						
Target	4.60	0.81	4.42	0.50	4.44	0.73
Prime	6.34	0.84	4.80	0.80	4.50	0.70
Frequency[a]						
Target	3.61	1.39	4.07	1.43	4.01	1.0
Prime	3.19	1.34	4.14	1.43	3.71	1.1
Neighborhood (N)[b]						
Target	6.00	4.48	7.38	4.01	7.94	4.45
Prime	3.97	2.43	4.79	4.04	7.83	5.08
Prime–Target Overlap (%)						
Orthography[c]	73	8	64	17	64	21
Phonemes	76	5	58	14	70	5
Stem	100	0	68	23	64	20
	Morphologically Unrelated					
	Phonological (Dollar–Doll)		*Semantic (Cherry–Grape)*		*−M + P + S (Scrape–Scratch)*	
	M	*SD*	*M*	*SD*	*M*	*SD*
Length						
Target	3.68	0.64	4.65	0.88	5.52	1.22
Prime	4.85	0.86	4.59	1.05	6.07	1.11
Frequency[a]						
Target	3.86	1.45	4.08	1.15	1.67	1.68
Prime	3.82	1.34	3.91	1.11	1.11	1.40
Neighborhood (N)[b]						
Target	10.94	5.63	5.91	4.78	2.81	3.08
Prime	5.71	4.27	7.15	7.11	1.63	3.28
Prime–Target Overlap (%)						
Orthography[c]	69	11	14	17	56	20
Phonemes	70	9	12	16	63	16

[a]Log-frequency of values from CELEX.

[b]Number of orthographic neighbors from *N*-watch.

[c]Number of letters shared in the same position between prime and target.

items were presented in uppercase 500 msec after the pattern mask and appeared on the screen for 5000 msec or until a response was made. Primes and targets were presented in different cases to minimize priming effects strictly due to physical similarity of the items. Participants indicated whether the visual target was an English word via a keypress.

ERP Recording and Analyses

EEGs were recorded from 64 Ag/AgCl sintered electrodes placed according to the International 10–20 System using a placement cap. Vertical and horizontal eye movements were recorded for later off-line artifact rejection by placing electrodes above and below the left eye and over the outer canthi. All impedances were kept at or below 5 KΩ. Signals were recorded at 500 Hz, referenced to nose-tip, with a band-pass filter of 0.1–100 Hz and a 60-Hz notch filter. Trials were divided in to epochs from 100 pre- to 800 msec posttarget stimulus onset, baseline-corrected to the pretrial interval, and low-pass filtered at 20 Hz (24 dB/oct zero phase-shift digital filter). Trials were excluded if they contained EOG activity exceeding ±75 μV, or corresponded to an incorrect behavioral response.

The mean N400 amplitudes of each trial were quantified within "early" and "late" time windows by computing mean amplitudes at 324–400 msec ("early") and 400–476 msec ("late"). An initial inspection of electrodes across the scalp, corroborated by the results of previous N400 studies (e.g., Münte et al., 1999), revealed that the largest N400 effects were seen in midline, central, and parietal sites. Therefore, electrodes were averaged into left, right, and midline frontal (LF, RF, FC), central (LC, RC, CC), and parietal (LP, RP, PC) regions for statistical analyses (Figure 1). Data from all scalp electrodes were used for visualization of the effects via isovoltage maps.

An earlier N2 component was also analyzed by computing mean amplitudes at 180–236 msec. Prior ERP studies of word recognition indicate that this component can be sensitive to priming when primes are masked (Lavric, Clapp, & Rastle, 2007; Morris, Frank, Grainger, & Holcomb, 2007). However, because primes were presented for relatively long duration and were not forward-masked, this effect is not expected to be as strong in the present experiment.

Separate repeated measure ANOVAs were performed on mean amplitudes at each time interval for the effects of priming (primed vs. unprimed), word type (regular, suffixed irregular, vowel-change irregular, ortho/phonological, semantic, −M + P + S), and electrode region (CC, FC, PC, LC, RC, LP, RP). Huynh–Feldt correction for sphericity violations was applied to ERP analyses for factors with more than two *df* in the numerator (reported are the original degrees of freedom and the corrected *p* values). Because this experiment compared priming effects for different degrees of morphological regularity and also form and meaning based priming, of main interest was the interaction between prime and word type at each interval. Thus,

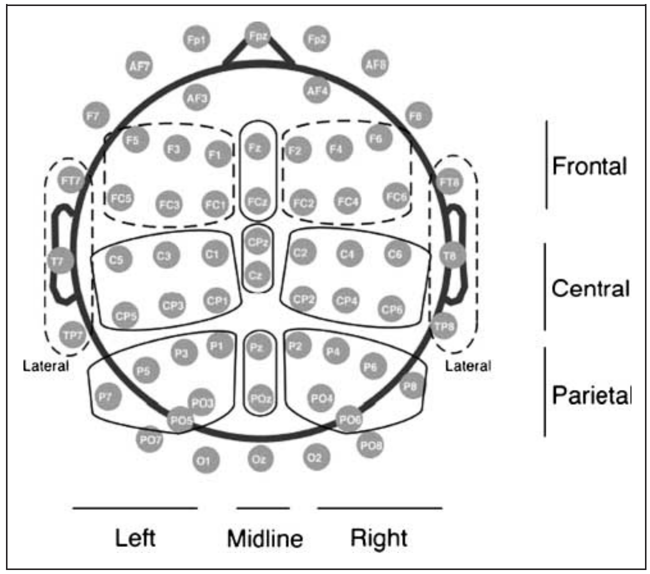


Figure 1. The 64-channel montage representing grouping of the electrodes into 11 regions. The data from seven electrode regions indicated by the solid line were used in the analyses: CC (Cz, CPz), FC (Fz, FCz), PC (Pz, POz), LC (C5, C3, C1, CP5, CP3, CP1), RC (C2, C4, C6, CP2, CP4, CP6), RP (P2, P4, P6, P8, PO4, PO6), LP (P1, P3, P5, P7, PO3, PO5). Midline regions: CC, FC, PC; central regions: RC, LC; and parietal regions: LP, RP. The data from the other electrodes indicated by the broken line were used for visualization of the effect using isovoltage maps: RF (F2, F4, F6, F8, FC2, FC4, FC6); LF (F7, F5, F3, F1, FC5, FC3, FC1); RT (FT8, T8, TP8); LT (FT7, T7, TP7).

significant interactions were followed up by a series of planned comparisons comparing related and unrelated words for each condition separately at each time interval. The planned comparisons consisted of repeated measures ANOVAs on mean amplitudes at midline (CC, FC, PC), central (LC, RC), and parietal (LP, RP) regions.

Difference waves (unprimed − primed) were also computed in order to measure the magnitude of priming effects for each condition. Mean amplitudes were computed using the average across the seven electrode regions, and compared across word type conditions using repeated measures ANOVAs and planned comparisons, as above. Additionally, a separate set of ANOVAs was conducted on the difference waves comparing each condition's early versus late mean amplitude values across all seven regions.

Results

Behavioral Results

Mean response latencies and error rates are presented in Table 2. Incorrect responses and RTs ±3 *SD* from the mean were removed and treated as errors. The ortho/phonological target *mast* and −M + P + S target *ghoul* were also excluded from the analyses based on error rates greater than 25% across participants. Statistical tests performed on behavioral and ERP data are presented in Table 3. For RTs, a

Table 2. Mean Latency (msec) (*SD*) and Accuracy (%) (*SD*) for Visual ERP Experiment

	RT		*Accuracy*	
Condition	*M*	*SD*	*M*	*SD*
Regulars				
Primed	538	41	99	2
Unprimed	593	46	98	3
Difference	+55**		1	
Suffixed Irregulars				
Primed	541	64	100	1
Unprimed	600	78	99	2
Difference	+58**		+1	
Vowel-change Irregulars				
Primed	550	56	99	2
Unprimed	570	47	99	2
Difference	+21		0	
Semantic				
Primed	545	56	99	2
Unprimed	567	62	99	2
Difference	+22**		0	
Phonological				
Primed	566	51	98	3
Unprimed	584	54	97	4
Difference	+17*		+1	
−M +P +S				
Primed	611	41	96	4
Unprimed	635	67	97	4
Difference	+23		−1	

*$p < .05$.
**$p < .01$.

Table 3. Statistical Tests Performed on Behavioral and ERP Data in Experiment 1

Variable	*Source*		*df*	*F*	*p*
RT	Word type (W)	F_1	5, 65	15.51	<.01
		F_2	5, 182	8.74	<.01
	Priming (P)	F_1	1, 13	34.31	<.01
		F_2	1, 182	52.49	<.01
	W × P	F_1	5, 65	3.90	<.01
		F_2	5, 182	2.35	<.05
Accuracy	Word type (W)	F_1	5, 65	6.98	<.01
		F_2	5, 182	4.69	<.01
	Priming (P)	F_1	1, 13	0.17	*ns*
		F_2	1, 182	0.80	*ns*
	W × P	F_1	5, 65	0.97	*ns*
		F_2	5, 182	0.36	*ns*
N2	Electrode (E)		6, 78	31.03	<.01
	Word type (W)		5, 65	1.13	*ns*
	Priming (P)		1, 13	8.79	<.05
	P × W		5, 65	1.67	*ns*
	P × E		6, 78	1.74	*ns*
	E × W		30, 390	.43	*ns*
	E × P × W		30, 390	1.12	*ns*
Early N400	Electrode (E)		6, 78	3.79	<.05
	Word type (W)		5, 65	3.16	<.05
	Priming (P)		1, 13	8.64	<.05
	P × W		5, 65	2.59	<.05
	P × E		6, 78	3.07	<.05
	E × W		30, 390	1.39	*ns*
	E × W × P		30, 390	0.70	*ns*
Late N400	Electrode (E)		6, 78	2.50	*ns*
	Word type (W)		5, 65	3.90	<.01
	Priming (P)		1, 13	11.51	<.01
	P × W		5, 65	4.13	<.01
	P × E		6, 78	2.60	<.05
	E × W		30, 390	1.39	*ns*
	E × W × P		30, 390	0.61	*ns*

repeated measures ANOVA, with prime and word type as within-subject factors, revealed significant main effects of prime, word type, and a Prime × Word type interaction (see Table 3). The results suggest conditions differed in the magnitude of priming effects. This was confirmed by planned comparisons revealing significant facilitation for regular and suffixed irregular verbs [regulars: $F_1(1, 13) = 29.83$, $p < .01$, $F_2(1, 34) = 23.00$, $p < .01$; suffixed: $F_1(1, 13) = 19.56$, $p < .01$, $F_2(1, 23) = 20.46$, $p < .01$], but not for vowel-change irregulars [$F_1(1, 13) = 4.46$, $p = .055$, $F_2(1, 35) = 3.49$, $p = .070$]. The comparison of the magnitude of priming effects for verb conditions revealed that the priming effects for regulars and suffixed irregulars did not differ from one another (all *F*s < 1). However, both produced a greater effect than vowel-change irregulars [regulars vs. v/c irregulars: $F_1(1, 13) = 7.24$, $p < .05$,

$F_2(1, 69) = 4.92, p < .05$; suffixed vs. v/c irregulars; $F_1(1, 13) = 4.53, p = .053, F_2(1, 58) = 4.59, p < .05$].

The size of priming effects also differed among the nonmorphological conditions. Significant facilitation was found for the semantic [$F_1(1, 13) = 18.59, p < .01, F_2(1, 33) = 8.33, p < .01$] and ortho/phonologically related words [$F_1(1, 13) = 6.42, p < .05, F_2(1, 32) = 3.28, p = .079$], but the priming effect for −M + P + S condition did not reach significance [$F_1(1, 13) = 3.01, p > .05, F_2(1, 25) = 3.46, p > .05$]. (Note that, in comparison to our previous study (Kielar et al., 2008), stronger effects for semantically and formally related words were found in the present experiment, indicating that formal overlap contributed to priming effects. This appears to be due to differences in the duration of the prime–target SOA and the masking procedure used.)

Accuracy. A similar analysis of accuracy data revealed a main effect of word type, but no main effect of prime or Prime × Word type interaction (see Table 3).

ERP Results

Figure 2 illustrates grand-average ERPs to primed versus unprimed verbs for each word type; the scalp extents of priming effects (primed−unprimed) are illustrated as isovoltage maps in Figure 3. Statistical analyses of the ERP data are listed in Table 3.

N2 interval. The first ANOVA tested for priming effects at 180–236 msec poststimulus onset. We observed a main effect of electrode region, and priming (see Table 3).

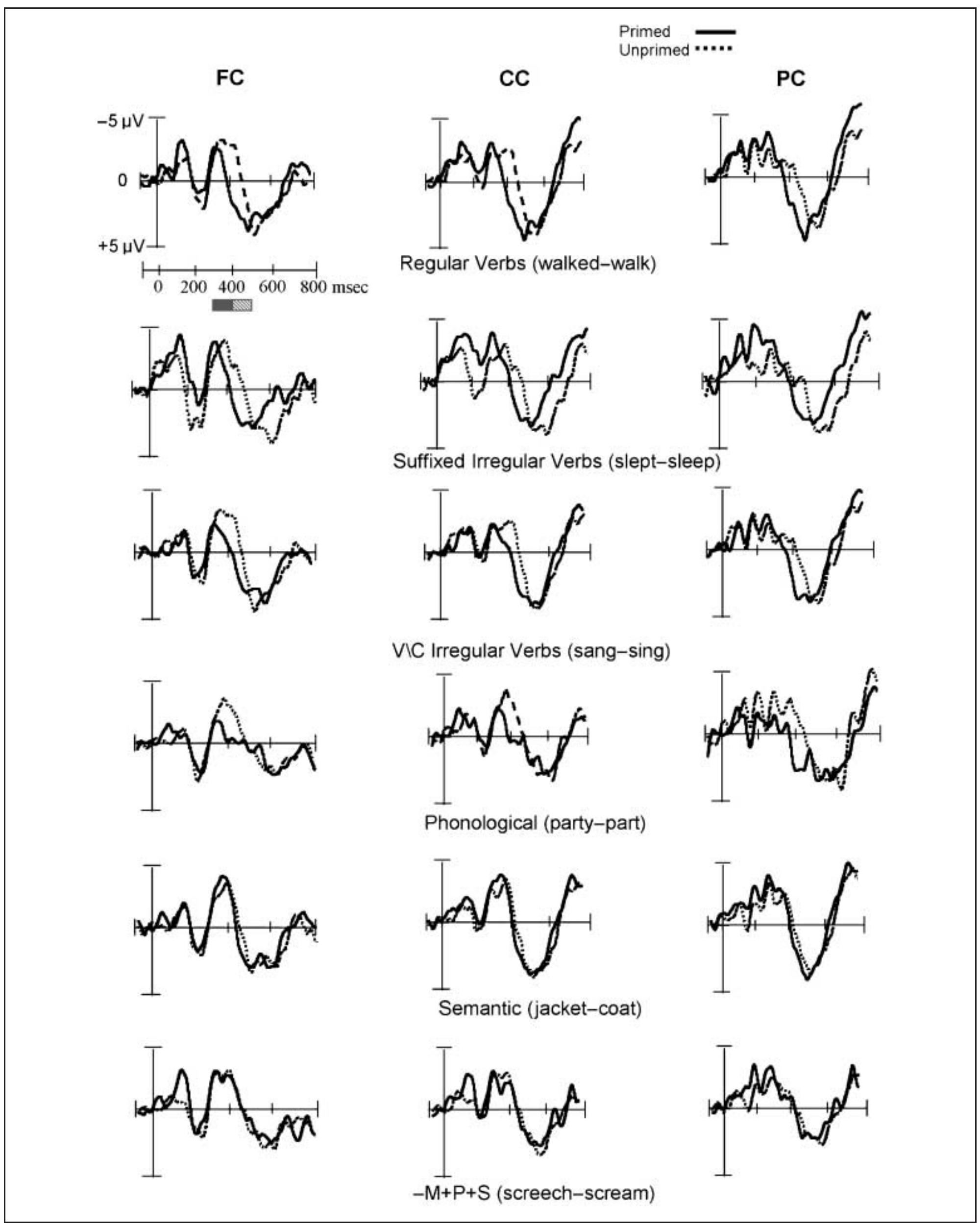


Figure 2. N400 results for each word type in visual ERP experiment. Grand-average ERPs (n = 14) elicited by primed and unprimed words at the midline regions (FC, CC, PC).

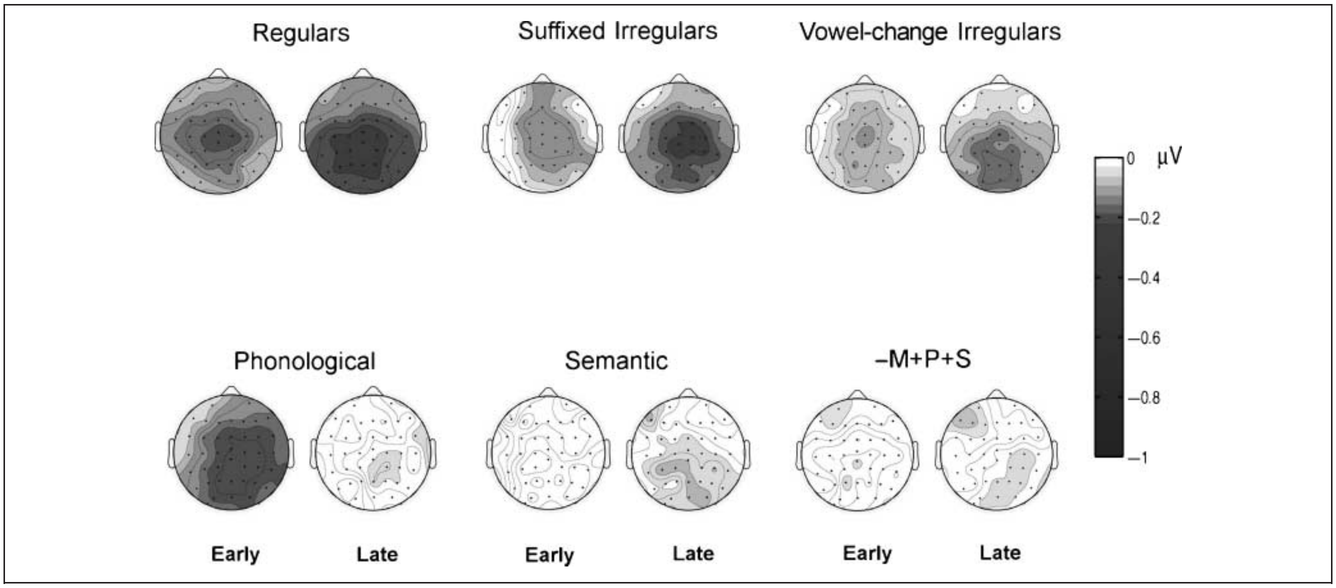


Figure 3. Topographical distribution of N400 priming effects across the scalp based on the difference waveforms (unprimed − primed), at early (342–400 msec) and late (400–476 msec) time intervals.

Planned comparisons revealed that the mean amplitude of primed versus unprimed targets only differed for the suffixed irregulars, but the effect was in the opposite direction as expected for priming [significantly more negative N2 for the primed compared to the unprimed condition, $F(1, 13) = 7.06$, $p < .05$]. No other conditions showed an effect at this time interval [regulars: $F(1, 13) = 2.10$, $p > .05$; irregulars, phonological, $-M + P + S$: all Fs < 1; semantic: $F(1, 13) = 2.72$, $p > .05$].

Early N400 interval. We observed a significant main effect of prime, word type, and also a Prime × Word type interaction (Table 3). The significant main effect of electrode region, and significant Region × Prime interaction, indicated that, overall, the priming effects were the greatest at the midline–central and parietal regions (Figure 2). Planned comparisons of amplitudes for primed versus unprimed targets were significant for the regular verbs [$F(1, 13) = 19.94$, $p < .01$] and the ortho/phonological condition [$F(1, 13) = 23.20$, $p < .01$]; no other comparisons were significant [vowel-change irregulars: $F(1, 13) = 2.79$, $p > .05$; suffixed irregulars: $F(1, 13) = 1.57$, $p > .05$; semantic and $-M + P + S$: both Fs < 1]. N400 priming magnitudes are plotted for each condition at the midline region (CC) in Figure 4. Planned comparisons of these waveforms across verb conditions (using mean amplitude of the primed–unprimed difference waves at this time interval) revealed no significant differences (all Fs < 1).

Late N400 interval. The ANOVA revealed a significant main effect of prime, word type, and a Prime × Word type interaction (see Table 3). There was a significant Electrode region × Prime interaction, reflecting larger priming effects at midline central and parietal regions (see Figure 2B for distribution of priming effects across the scalp).

Planned comparisons were performed on the mean amplitudes for primed versus unprimed targets for each word condition, and revealed significant N400 priming for regular verbs [$F(1, 13) = 32.51$, $p < .01$], vowel-change irregulars [$F(1, 13) = 7.76$, $p < .05$], and suffixed irregulars [$F(1, 13) = 6.53$, $p < .05$], but not for the ortho/phonological [$F(1, 13) = 1.41$, $p > .05$], semantic [$F(1, 13) = 1.32$, $p > .05$], or $-M + P + S$ conditions ($F < 1$). As at the early time interval, the comparison difference waves (primed − unprimed) revealed no significant differences in mean amplitudes among verb conditions at this time interval [regulars vs. vowel-change irregulars: $F(1, 13) = 2.50$, $p > .05$; regulars vs. suffixed irregulars: $F(1, 13) = 4.05$, $p > .05$; vowel-change irregulars vs. suffixed irregulars: $F < 1$].

The inspection of ERP waveforms suggested a temporal element to the ortho/phonological results. To investigate this effect, a repeated measures ANOVA with interval, electrode region, and word type as within-subject variables was conducted on the mean amplitudes of the difference waves. This analysis revealed a significant main effect of word type [$F(5, 65) = 3.39$, $p < .01$] and an interaction between interval and word type [$F(5, 65) = 2.86$, $p < .05$]. Follow-up analyses of the interaction confirmed that the N400 priming effect for the ortho/phonological condition was significantly greater in the earlier versus later time interval [$F(1, 13) = 7.28$, $p < .05$], whereas no other conditions showed an effect [regulars: $F(1, 13) = 4.18$, $p > .05$; suffixed irregulars: $F(1, 13) = 1.05$, $p > .05$; vowel-change irregulars, semantic, and $-M + P + S$: $F < 1$].

Discussion

Visual priming was used to investigate ortho/phonological and semantic influences on ERP priming of past tense verbs. The results are similar to previous ERP studies in that we did find significant N400 priming effects for regular verbs (Rodriguez-Fornells et al., 2002; Münte et al., 1999; Weyerts et al., 1996). Likewise, consistent with a recent study by Justus et al. (2008), we also found significant ERP priming for irregular verbs. Thus, the results illustrate the presence of morphological priming effects that are not uniquely related to rule-like forms.

The results seem to suggest that priming effects reflect the joint contribution of formal (orthophonological) similarity and semantic relatedness, rather than the mere presence of one or the other. Moreover, the temporal changes in N400 priming effects suggest different processing elements change over time. The early time interval appears to reflect the formal relationship between prime and target, marked by priming for ortho/phonological and

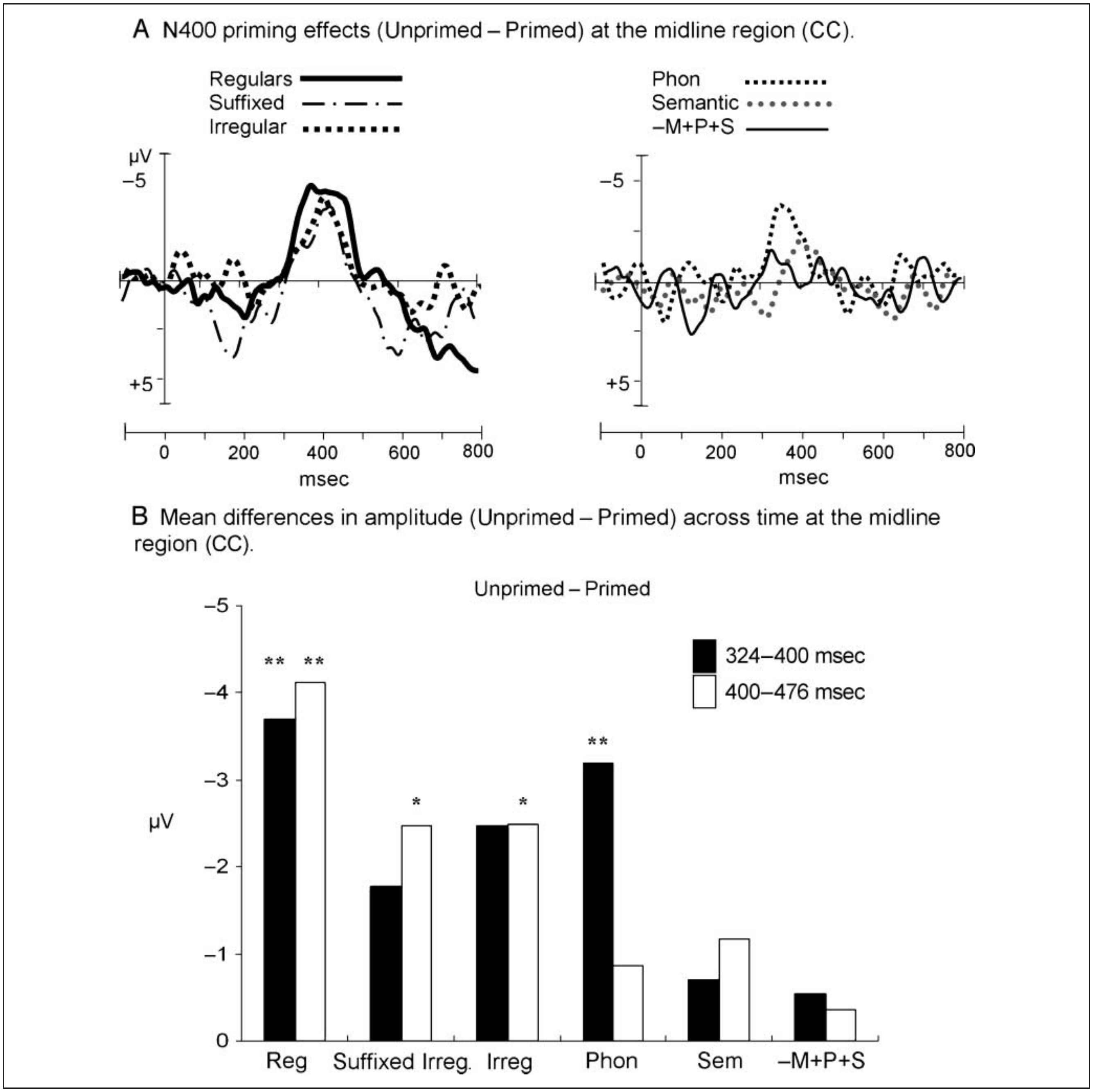


Figure 4. N400 priming results in visual ERP experiment. (A) Difference waves (unprimed − primed) at the midline region (CC). The difference waves illustrate the electrophysiological effect of priming for each word type. (B) Mean differences in amplitude (unprimed − primed) for all conditions at the midline region (CC) in 324–400 msec and 400–476 msec time intervals.

regular past tense pairs. This is consistent with behavioral studies showing a stronger influence of formal overlap in the early stages of morphological processing (Feldman et al., 2004; Rastle, Davis, & New, 2004; Feldman, 2000). At the later N400 time interval, this effect disappeared and priming was observed only for morphologically related forms (regulars and irregulars).

Importantly, the results at this later interval do not appear to be attributable strictly to semantic overlap; ERP priming effects were not found for items that were only related in terms of semantics (e.g., *couch–sofa*). This is admittedly surprising given earlier studies finding N400 semantic priming in visual lexical decision (Deacon et al., 2000; Brown & Hagoort, 1993; Holcomb & Neville, 1990; Bentin et al., 1985). However, such effects tend be influenced by stimulus list characteristics, such as the proportion of semantically related and unrelated word pairs in the stimulus set (Brown et al., 2000; Holcomb, 1988). In the present study, only a small proportion of prime–target pairs shared a purely semantic relationship (18% of word items); moreover, the three morphologically related lists consisted of present–past pairs that were very closely related in terms of form. This may have led the word recognition system to tune more to the formal characteristics of items and less to the semantic relationship between words (Tweedy, Lapinski, & Schvaneveldt, 1997; Holcomb, 1986, 1988; Napps & Fowler, 1987; de Groot, 1984).

We did not find N400 priming for −M + P + S items (*screech–scream*), which were related in form and meaning but did not share morphemes. This is somewhat surprising given prior behavioral data suggesting morphological-like priming effects for such items (Bergen, 2004). The failure to find effects is perhaps due to the lower degree of orthographic overlap between primes and targets for these items (56% overlapping letters) compared to the verb conditions. In addition, prime–target pairs in the phonological and verb conditions had overlapping word onsets, whereas this occurred to a lesser extent in the −M + P + S pairs, which again could lead to weaker priming (Pastizzo & Feldman, 2002a).

Some earlier studies have found morphological priming effects in the N2 component (Lavric et al., 2007; Morris et al., 2007), using short-lag masked priming in the visual modality. Such effects have been attributed to orthographic decomposition processes in reading. We failed to observe similar effects in this study, however; only one condition showed a primed versus unprimed difference, but in the opposite direction (i.e., increased negativity for priming). The absence of N2 priming effects appears to be due to the fact that primes were not fully masked and were presented at a longer SOA. Importantly, however, orthographic effects were evident in our analyses of the early N400 component, confirming that the experiment was sensitive to the contribution of this factor, albeit at a different point in the ERP waveform.

We also noted that RT results diverged somewhat from the ERP results. First, a significant behavioral priming effect was found for regulars and suffixed irregulars, but just missed significance for vowel-change irregulars. This might suggest that, in the present study, the ERP measures were generally more sensitive to subtle priming effects than the RT measure. More problematic to this view is the finding that significant priming was found for the semantic conditions in RTs, but not in the ERP data. This is not the first study to find dissociations between behavioral and N400 priming effects however (Jescheniak, Schriefers, Garrett, & Friederici, 2002; Rodriguez-Fornells et al., 2002; Kellenbach, Wijers, & Mulder, 2000; Münte et al., 1999; Brown & Hagoort, 1993; Hamberger & Friedman, 1992). The data suggest that N400 amplitude and lexical decision response latencies reflect partially independent cognitive processes that may not be sensitive to the same stages of word analysis. The N400 effects examined in the present study represent an intermediate stage of word analysis occurring prior to response selection. In contrast, the RT effects reflect the outcome of information processing that extends beyond the ERP components of interest here.

EXPERIMENT 2: CROSS-MODAL PRIMING

Experiment 1 found priming effects for both regular and irregular forms, although these effects were at least partly influenced by formal overlap. The visual priming paradigm also made it difficult to distinguish between orthographic and phonological influences, which are closely correlated in English. Experiment 2 addressed these issues by examining priming using cross-modal presentation. Participants heard the prime as a spoken word, but still performed a lexical decision on a visual target. The resulting facilitation effects are thought to be mediated through a modality-independent level of processing, minimizing the influence of orthographic overlap (Longtin, Segui, & Halle, 2003; Allen & Badecker, 2002; Frost et al., 2000; Marslen-Wilson, Komisarjevsky-Tyler, Waksler, & Older, 1994). On the single-mechanism view, this corresponds to the idea that the prime engages phonological information directly rather than via orthographic codes. It is possible that reducing the role of visual and orthographic overlap might lead to priming effects that are unique to regular past tenses, consistent with what would be predicted by a dual-mechanism approach. Also of interest was whether this manipulation would better emphasize sound–meaning consistencies, leading to stronger priming effects for the −M + P + S condition, consistent with a single-mechanism/connectionist view.

Methods

Participants

Fifteen right-handed native speakers of English, ages 19–30 years (M = 24, SD = 4) participated. All procedures were approved by the University of Western Ontario Non-Medical Research Ethics Board and the University of Western Ontario Department of Psychology Research

Ethics Board. All participants were students at the University of Western Ontario, had normal (or corrected-to-normal) vision, and no history of neurological or psychiatric illness. The participants received 2 hours of course credit or $20 for participating in the study.

Materials and Procedure

The stimulus items in each experimental condition were the same as in Experiment 1. However, we did modify the filler items such that these lists consisted only of word prime–nonword target pairs, to reduce testing time (note, however, that each prime condition continued to include its own unrelated word–target items). In order to avoid strategic effects due to stimulus predictability, the filler condition included trials on which nonword targets were preceded by auditory primes that were past tense verbs (e.g., *printed–DRASS*), present tense verbs (e.g., *blend–DASE*; *stamping–TRINK*), nouns (e.g., *brain–DEST*), and adjectives or adverbs (e.g., *humble–MEST*, *nicely–RIVE*). The number of nonword filer trials was increased to 400, which preserved the proportion of related to unrelated trials across both experiments.

On each trial, a fixation cross was displayed at the center of a computer screen while the auditory prime was presented over earphones at a comfortable listening level. Following a 500-msec delay, the visual target was presented in uppercase letters. Targets appeared for 5000 msec or until a response was made. Participants performed lexical decisions to targets by pressing a key on a response pad. Trial order was randomized as in Experiment 1, such that order of primed versus unprimed word presentations was counterbalanced across subjects. All EEG recording procedures, materials, and analyses were the same as in Experiment 1.

Results

Behavioral Results

Mean response latencies and error rates are presented in Table 4. Incorrect responses and RTs ±3*SD* from the mean were removed and treated as errors. The targets *mast* and *earl* (ortho/phonological condition) and *slink* (−M + P + S condition) were excluded from analyses based on error rates greater than 25% across participants.

Statistical tests of behavioral and ERP data are presented in Table 5. For RTs, a repeated measures ANOVA with prime and word type as within-subject factors revealed significant main effects of prime, word type, and a Prime × Word type interaction, indicating the magnitude of priming effects was not equivalent for all conditions. Planned comparisons revealed significant facilitation for all morphologically related conditions [regulars: $F_1(1, 14) = 40.03$, $p < .01$, $F_2(1, 34) = 55.03$, $p < .01$; suffixed irregulars: $F_1(1, 14) = 13.04$, $p < .01$, $F_2(1, 23) = 20.59$, $p < .01$; vowel-change irregulars: $F_1(1, 14) = 10.99$, $p < .01$, $F_2(1, 35) = 20.35$, $p < .01$]. The comparison of priming effects for verb conditions revealed that suffixed irregulars did not differ from regulars or vowel-change irregulars [suffixed irregulars vs. regulars: $F_1(1, 14) = 3.19$, $p > .05$, $F_2(1, 57) = 3.43$, $p > .05$; suffixed vs. v/c irregulars: both *F*s < 1]. However, the effect for regulars was significantly greater than that for vowel-change irregular verbs [$F_1(1, 14) = 12.53$, $p < .01$, $F_2(1, 69) = 6.66$, $p < .05$]. For the morphologically unrelated words, the −M + P + S condition showed significant facilitation [$F_1(1, 14) = 16.57$, $p < .01$, $F_2(1, 25) = 15.65$, $p < .01$], but the priming effects for the ortho/phonologically and semantically related words were not significant

Table 4. Mean Latency (msec) (*SD*) and Accuracy (%) (*SD*) for CM ERP Experiment

	RT		*Accuracy*	
Condition	*M*	*SD*	*M*	*SD*
Regulars				
Primed	535	76	100	1
Unprimed	591	82	97	4
Difference	+55**		+3	
Suffixed Irregulars				
Primed	549	81	99	2
Unprimed	583	79	97	4
Difference	+34**		+2	
Vowel-change Irregulars				
Primed	550	72	99	1
Unprimed	579	81	99	2
Difference	+28**		0	
Semantic				
Primed	570	69	100	1
Unprimed	577	78	97	4
Difference	+7		+3	
Phonological				
Primed	582	68	98	4
Unprimed	587	70	96	4
Difference	+5		+2	
−M + P + S				
Primed	613	83	96	5
Unprimed	647	99	94	6
Difference	34**		+2	

**$p < .01$.

(all *F*s < 1). These results replicate findings previously reported in a larger sample (Kielar et al., 2008).

Accuracy. The analysis of accuracy data revealed a significant main effect of prime and word type, but no interaction (Table 5).

Table 5. Statistical Tests Performed on Behavioral and ERP Data in Experiment 2

Variable	*Source*		*df*	*F*	*p*
RT	Word type (W)	F_1	5, 70	26.97	<.01
		F_2	5, 181	14.11	<.01
	Priming (P)	F_1	1, 14	33.19	<.01
		F_2	1, 181	83.03	<.01
	W × P	F_1	5, 70	5.56	<.01
		F_2	5, 181	6.14	<.01
Accuracy	Word type (W)	F_1	5, 70	8.06	<.01
		F_2	5, 181	5.90	<.01
	Priming (P)	F_1	1, 14	15.43	<.01
		F_2	1, 181	20.19	<.01
	W × P	F_1	5, 70	0.73	*ns*
		F_2	5, 181	0.83	*ns*
N2	Electrode (E)		6, 84	12.32	<.01
	Word type (W)		5, 70	6.12	<.01
	Priming (P)		1, 14	1.44	*ns*
	P × W		5, 70	0.29	*ns*
	P × E		6, 84	4.31	<.01
	E × W		30, 420	2.59	<.01
	E × P × W		30, 420	0.74	*ns*
Early N400	Electrode (E)		6, 84	1.77	*ns*
	Word type (W)		5, 70	4.09	<.05
	Priming (P)		1, 14	15.36	<.01
	P × W		5, 70	3.21	<.05
	P × E		6, 84	7.52	<.01
	E × W		30, 420	2.14	<.05
	E × W × P		30, 420	1.26	*ns*
Late N400	Electrode (E)		6, 84	11.52	<.01
	Word type (W)		5, 70	14.47	<.01
	Priming (P)		1, 14	12.03	<.01
	P × W		5, 70	2.08	*ns*
	P × E		6, 84	5.92	<.01
	E × W		30, 420	2.54	<.05
	E × W × P		30, 420	1.26	*ns*

ERP Results

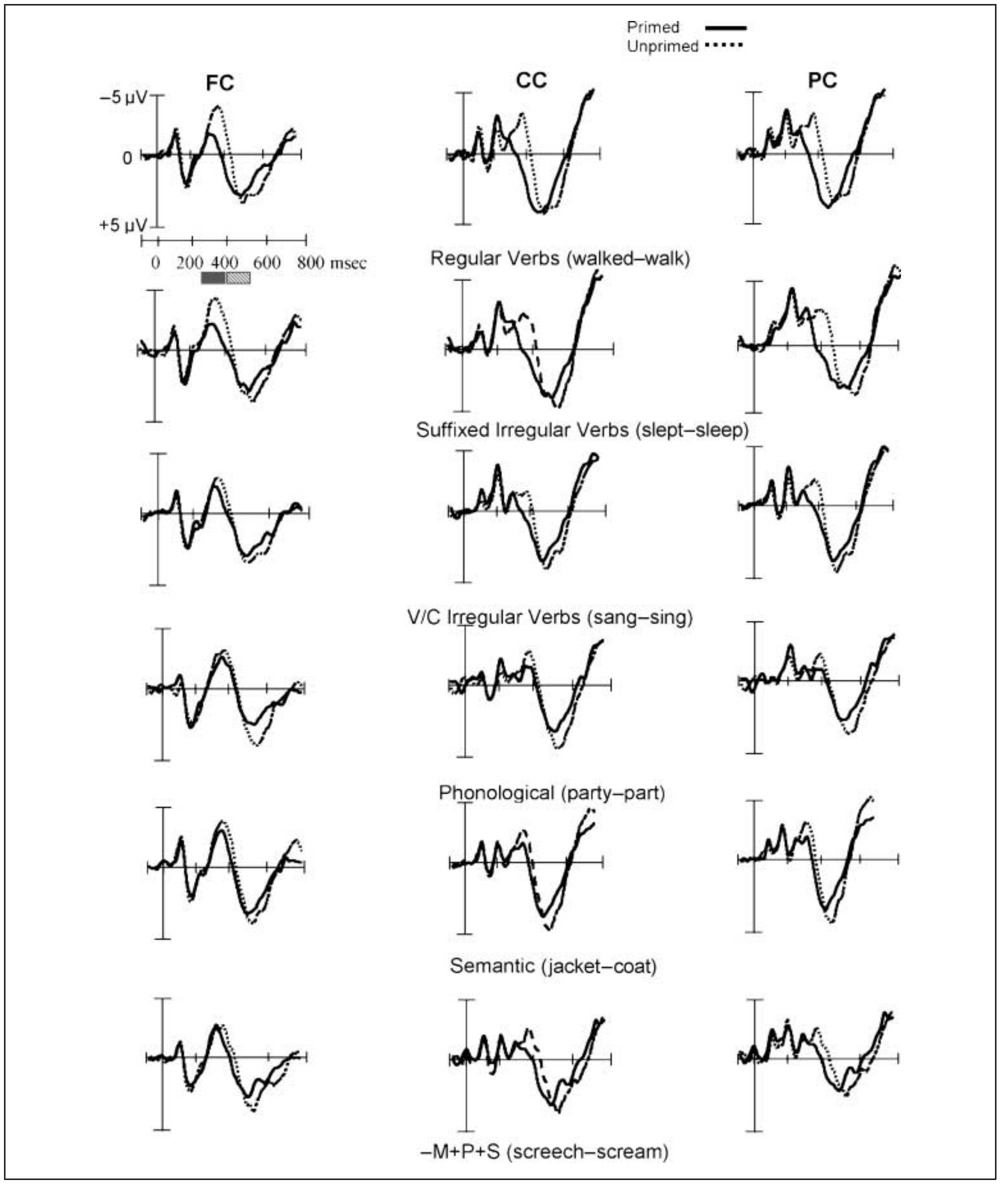
Grand-average ERPs for each condition are illustrated in Figure 5. Figures 6 and 7 illustrate the topographical distributions and amplitudes of N400 priming effects, respectively.

N2 interval. A repeated measures ANOVA with prime, word type, and electrode region as within-subject factors examined effects at the 180–236 msec interval. This revealed a main effect of electrode region and word type. There were significant interactions of Region × Prime, and Region × Word type (Table 5). The interaction of prime and region might be suggestive of a small N2 priming effect restricted for certain scalp regions; however, a post hoc analysis failed to reveal significant primed − unprimed differences for any conditions [regulars, irregulars, suffixed irregulars, semantic, −M + P + S, all *F*s < 1; phonological: $F(1, 14) = 1.72$, $p > .05$].

Early N400 interval. A repeated measures ANOVA revealed significant main effects of prime and word type. The Prime × Word type interaction was significant, as was Electrode region × Prime and Region × Word type. Planned comparisons on the mean amplitude of primed versus unprimed targets revealed significant N400 priming effects for all verb conditions at the early interval [regulars: $F(1, 14) = 17.86$, $p < .01$; suffixed irregulars: $F(1, 14) = 5.79$, $p < .05$; vowel-change irregulars: $F(1, 14) = 4.68$, $p < .05$]. Significant priming effects were also found for the semantic, −M + P + S, and ortho/phonological conditions [$F(1, 14) = 9.35$, $p < .01$; $F(1, 14) = 8.56$, $p < .05$; $F(1, 14) = 6.99$, $p < .05$]. Additionally, the comparison of the magnitude of priming effects for verb conditions, as indexed by mean amplitude of the difference waves, revealed significantly greater priming for regulars compared to vowel-change irregulars [$F(1, 14) = 17.21$, $p < .01$]. Suffixed irregulars showed an intermediate effect, such that they were not significantly different from regulars [$F(1, 14) = 2.92$, $p > .05$] or vowel-change irregulars [$F(1, 14) = 2.50$, $p > .05$].

Late N400 interval. There were significant main effects of prime, word type, and electrode region. Significant interactions were observed for Electrode region × Word type, and Region × Prime. Planned comparisons performed on the mean amplitudes of primed versus unprimed targets revealed significant priming effects for the regular, suffixed irregular, and −M + P + S conditions [regulars: $F(1, 14) = 13.23$, $p < .01$; suffixed irregulars: $F(1, 14) = 6.16$, $p < .05$, −M + P + S: $F(1, 14) = 6.36$, $p < .05$]. However, no priming effect was observed for the vowel-change irregulars [$F(1, 14) = 1.31$, $p > .05$], the semantic condition [$F(1, 14) = 3.36$, $p > .05$], or the ortho/phonological

Figure 5. N400 results for each word type in cross-modal ERP experiment. Grand-average ERPs (n = 15) elicited by primed and unprimed words at the midline region (FC, CC, PC).



condition ($F < 1$). Here again, the comparison of verb conditions using mean amplitude of the difference waves (unrelated − related) revealed differential effects for verbs, such that regulars showed greater priming effects than vowel-change irregulars [$F(1, 14) = 8.18, p < .05$]. As in the early time window, suffixed irregulars showed an intermediate effect, such that the priming effects for suffixed irregulars did not differ from regulars [$F(1, 14) = 1.80, p > .05$], or vowel-change irregulars [$F(1, 14) = 2.18, p > .05$].

Finally, an additional ANOVA with interval, site, and word type as within-subject variables computed on the mean amplitude of the difference waves (unrelated − related), compared priming effects at the early versus late N400 time intervals. This analysis revealed a significant main effect of word type [$F(5, 70) = 3.72, p < .01$], but no interaction between interval and word type [$F(5, 70) = 1.21, p > .05$], or three-way Interval × Electrode region × Word type interaction [$F(50, 700) = 1.50, p > .05$]. The comparison of priming effects for each condition across the two time intervals revealed a significantly greater effect for regulars at the early time window [$F(1, 14) = 4.62, p < .05$]; similar effects were marginal for the vowel-change irregular [$F(1, 14) = 3.80, p = .071$], suffixed irregular [$F(1, 14) = 3.69, p = .075$], and phonological conditions [$F(1, 14) = 3.64, p = .077$]. The effects across two time windows did not differ significantly for semantically related targets [$F(1, 14) = 2.65, p > .05$] or the −M + P + S condition ($F < 1$).

Discussion

ERP priming effects were compared for different degrees of morphological regularity, and for strictly meaning- and form-based priming. As expected, cross-modal presentation reduced the apparent effect of orthographic overlap observed in Experiment 1, and revealed stronger differences in the size of N400 priming for different morphologically related targets. At the early portion of the N400, significant priming effects were found for all conditions including the semantic, ortho/phonological, and −M + P + S conditions. However, at the later portion of the N400 component, this effect disappeared for vowel-change irregular verbs and the semantic and ortho/phonological conditions. Thus, the temporal characteristics of the ERP waveforms allowed us to tease apart effects of morphological, semantic, and phonological relatedness. As in Experiment 1, we did not find priming effects in the N2 component, which was not unexpected given that prior findings of this type have been restricted to short-SOA visual priming paradigms.

Of key theoretical interest was the observation that morphological effects were graded, such that we found greater priming for regular verbs, a smaller effect for vowel-change irregulars, and an intermediate effect for suffixed irregulars. This was most prominent at the later time interval, where priming was only found for regulars and suffixed irregulars and not vowel-change irregulars. This finding seems inconsistent with the theory that rule-based forms and irregulars are recognized via separate mechanisms, as predicted by a dual-mechanism account. Instead, this pattern seems to better fit the view that "regularity" is a strictly relative, rather than dichotomous, construct.

Just as importantly, the use of cross-modal priming suggests the observed morphological priming effects cannot be attributed to formal or semantic similarity alone. Specifically, the ortho/phonological condition showed appreciably smaller effects in this experiment compared to what was observed in visual–visual priming. In contrast, significant N400 priming effects were found for the −M + P + S condition, suggesting that the joint contribution of form and meaning representations can lead to facilitation for these items, especially when phonological similarity was enhanced under cross-modal presentation.

GENERAL DISCUSSION

Prior ERP studies have observed differential effects of morphological regularity in ERPs (Newman et al., 2007; Morris & Holcomb, 2005; Rodriguez-Fornells et al., 2001, 2002; Münte et al., 1999; Gross et al., 1998; Penke et al., 1997; Weyerts et al., 1997), which might support the theory that regular and irregular forms are processed via dissociable neurocognitive mechanisms. As we argued in the Introduction, however, there is an alternative theory that suggests morphology is an emergent characteristic of the interaction between phonological and semantic relatedness (Plaut & Gonnerman, 2000; Seidenberg & Gonnerman, 2000). On this view, dissociations occur in morphology due to the degree of formal overlap between related forms (Kielar et al., 2008), along with a form's phonological typicality (Burzio, 2002) and semantic characteristics (Baayen & Moscoso del Prado Martin, 2005). We examined this hypothesis with respect to past tense regularity, using ERP priming. In particular, we assessed the hypothesis that it is possible to observe graded effects of regularity in ERP priming by manipulating the ortho/phonological relationship between prime and target.

The key finding was that N400 priming effects are not unique to regular forms, but can extend to irregulars as well. Moreover, these effects do appear to be specific to morphology, in that priming was not observed for forms related only with respect to semantics, orthography, or phonology. These effects cannot be attributed to morphological decomposition processes, however, as they were

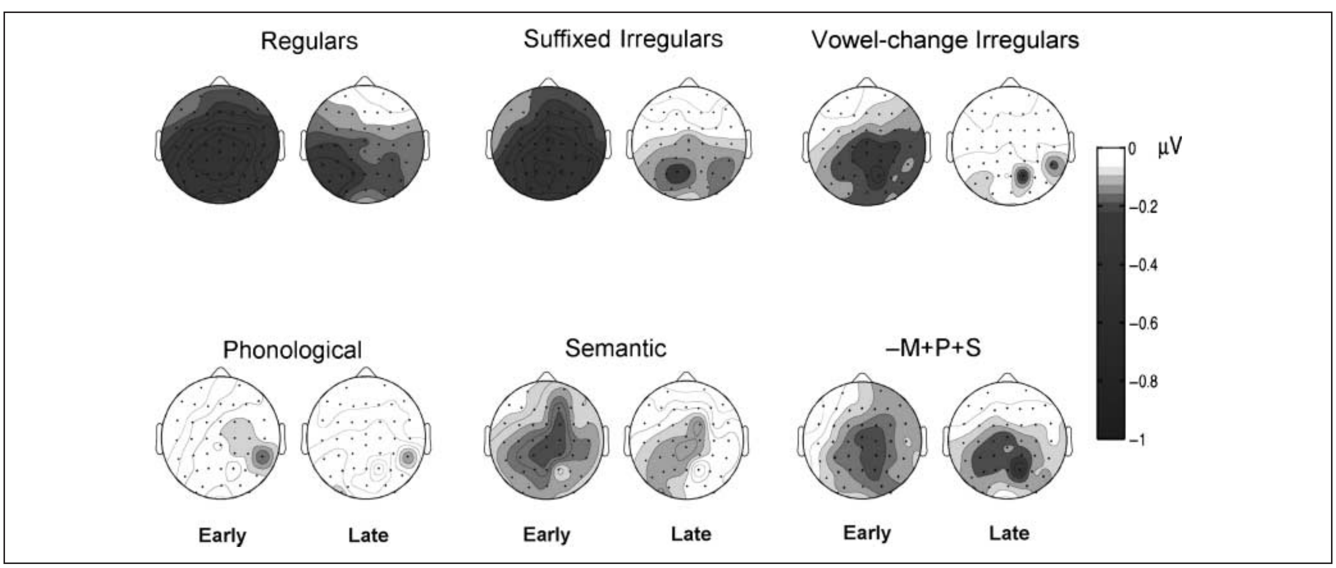


Figure 6. Topographical distribution of N400 priming effects across the scalp based on the differences waveforms (unprimed − primed), at early (324–400 msec) and late (400–476 msec) time intervals.

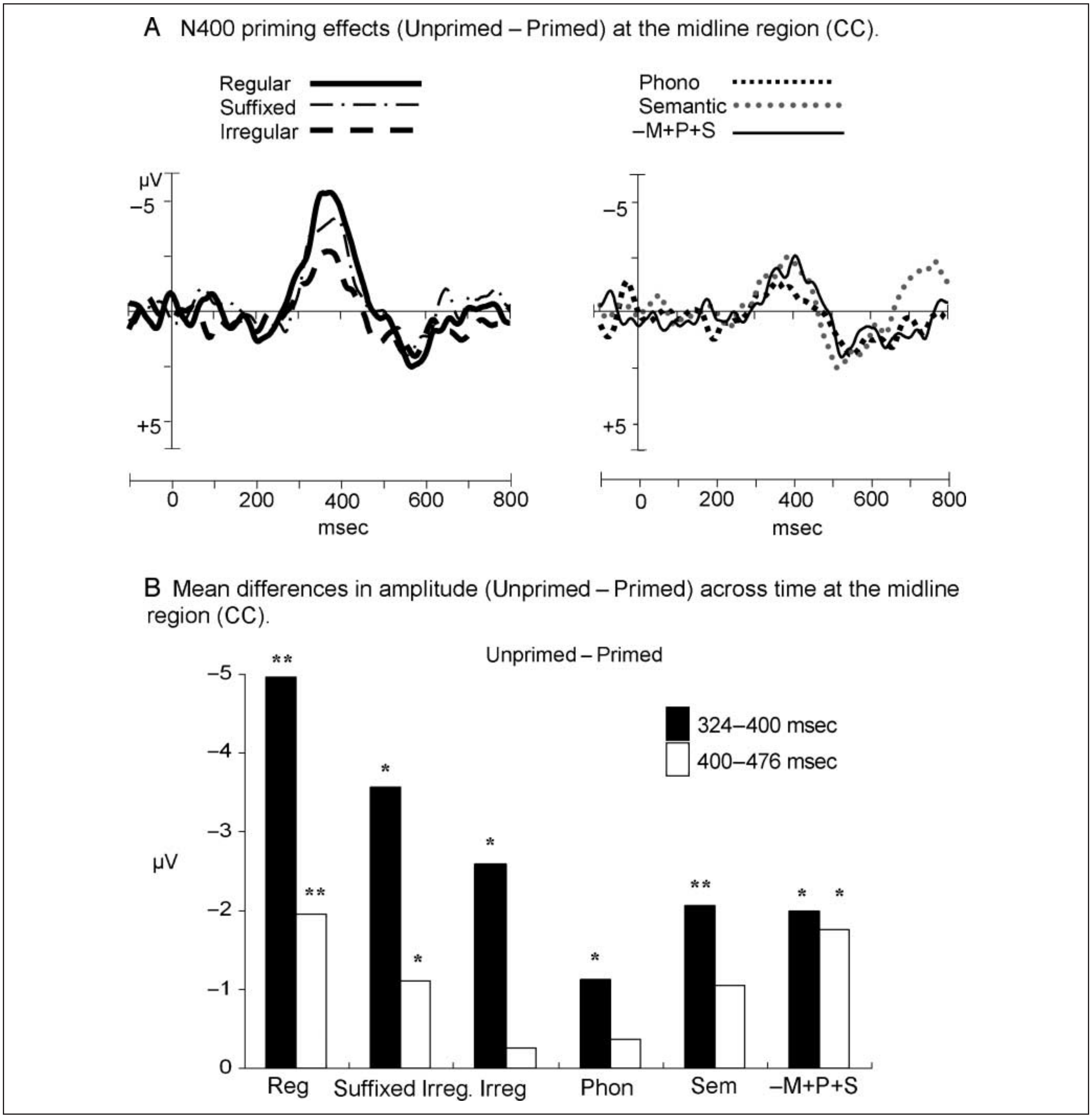


Figure 7. N400 priming results in cross-modal ERP experiment. (A) Difference waves (unprimed − primed) for each word type at the midline region (CC). The difference waves illustrate the electrophysiological effect of priming. (B) Mean differences in amplitude (unprimed − primed) for all word types at the midline region (CC) in 324–400 msec and 400–476 msec time intervals.

not specific to regular forms; rather, we interpret them as occurring due to the interaction of formal and semantic relatedness over the time course of word recognition (Plaut & Gonnerman, 2000).

The results also indicate that the degree to which formal and semantic dimensions of similarity influence word recognition changes over the time course of processing; hence, subtly different effects were observed when the N400 waveform was divided into "early" and "late" time windows. Furthermore, the contribution of both types of information varied as a function of the sensitivity of visual and cross-modal presentation modalities to the orthophonological and semantic properties of stimuli, leading to differences in N400 priming effects for visual–visual versus auditory–visual priming. In Experiment 1, orthophonological overlap seemed to have the greatest effect in the early time window, whereas the integration of semantic and formal factors influenced morphological effects in the later time window.

Thus, these results seem to fit well with previous findings of the time-varying influence of form and meaning information in recognizing morphologically complex words (Feldman et al., 2004; Feldman & Prostko, 2002; Feldman & Soltano, 1999).

Of particular interest was the finding that the degree of priming N400 for past tenses was modulated in a graded way, such that we found stronger priming for irregular forms that were more similar to regulars (the suffixed irregular condition) compared to the vowel-change irregulars. This pattern of effects is compatible with the results of the auditory immediate priming study reported by Justus et al. (2008). Their results showed stronger and more prolonged priming effects for strong (vowel-change) irregular verbs compared to weak irregulars and regulars. These results are consistent with the greater reliance of irregular verbs on semantic representations, an effect that was enhanced by the immediate priming design. They also reveal the effect of the inconsistent orthophonological relationship between present and past tense forms on priming effects. Consistent with our results, the orthophonological effects were observed in the early but not in the later time window, confirming the time-varying contribution of formal overlap to morphological processing.

In contrast with our data, Münte et al. (1999) previously found significant N400 priming for regulars only, and not for either irregulars or formally related words. This difference might be due to the fact that the present study used an immediate priming paradigm, which appeared to elicit generally stronger N400 effects compared to the long-lag paradigm used by Münte et al. It is possible that N400 effects for irregulars were simply too small to be detected in that study, due to the interitem lag of 5 to 13 items that was used. This might also explain why their study failed to find priming effects for formally related items. It does seem to be the case that when primes and targets are separated by intervening items, orthographic effects tend to be reduced or eliminated (Drews & Zwitserlood, 1995). In contrast, orthographically similar items produce reliable behavioral effects in a contiguous procedure where the target immediately follows the prime (Napps & Fowler, 1987).

The present results are also relevant to the results of ERP morphological priming studies conducted in other languages such as German (Weyerts et al., 1996) and Spanish (Rodriguez-Fornells et al., 2002), which found generally stronger effects for regular than irregular inflections. The results of the present study suggest that this dissociation might be due to orthographic and/or phonological similarity rather than morphological status; the key prediction is that a weaker advantage for regulars should be observed using either a more rapid presentation paradigm, or by comparing priming for irregulars that pattern more closely with regular items. A similar prediction is made for dissociations in ERPs for regulars and irregulars in morphological violation studies (Newman et al., 2007; Rodriguez-Fornells et al., 2001; Gross et al., 1998; Penke et al., 1997; Weyerts et al., 1997). Again, such effects may reflect the degree of phonological similarity between correct and incorrect forms, rather than a categorical distinction between regular and irregular inflections.

The contributions of formal and semantic dimensions of similarity to morphology have been also documented by the recent behavioral investigations of morphological priming with derivational-suffixed words (Marslen-Wilson, Bozic, & Randall, 2008; McCormick, Rastle, & Davis, 2008; Diependaele, Sandra, & Grainger, 2005; Longtin & Meunier, 2005; Rastle et al., 2000, 2004; Longtin et al., 2003; Dominguez et al., 2002). Moreover, a similar findings have been reported in the present N400 priming studies of suffixed derivations that attempted to tease apart effects of semantic, orthographic, and morphological priming to the visual word processing using long SOAs (Dominguez, de Vega, & Barber, 2004; Barber, Dominguez, & de Vega, 2002). The findings of the recent masked priming studies of derivational morphology (Lavric et al., 2007; Morris et al., 2007) are consistent with the early influence of form overlap, and with semantic overlap constraining morphological processing at the later stages of word recognition. Notably, the Morris et al. study also found graded effects of morphological relatedness consistent with the present results.

Conclusion

We argue that the present findings are consistent with the connectionist view that word recognition is achieved via the engagement of formal and semantic processes, that these processes unfold in different ways over time, and that morphology itself emerges as a consequence of the systematic mapping between these multiple codes (Kielar et al., 2008; Plaut & Gonnerman, 2000; Seidenberg & Gonnerman, 2000; Joanisse & Seidenberg, 1999; Rueckl, Mikolinski, Raveh, Miner, & Mars, 1997). On this view, every word is learned and processed in the context of many other words such that internal representations support the processing of all words, whether they are morphologically related or unrelated. Morphological representations are an emergent characteristic of this system, and occur because of statistical regularities arising in sound–meaning associations (e.g., *walk–walked* are related in the same way as *type–typed*). This can extend even to −M + P + S word pairs, which do not have clear morphological relationships but do have some degree of phonological and semantic consistency.

An important consequence of this view is that dissociations between different verb types are not a necessary consequence of rules per se, but can instead reflect differences in the representational codes used in recognizing words. This suggests that the distinction between regular and irregular verbs is a graded one, and that morphology is processed as a function of statistical regularities in the sound and meaning of words.

APPENDIX A

Prime and target pairs used in ERP priming experiments. Items matched for natural log-frequency values from CELEX, orthographic neighborhood (*N*-watch), orthographic length, and phonological and orthographic overlap.

Prime				*Target*					
Item	*Frequency*	*Length*	*N*	*Item*	*Frequency*	*Length*	*N*	*Phonological Overlap (% Phonemes)*	*Orthographic Overlap (% Letters)*
Regular Verbs									
rented	2.3	6	4	rent	3.8	4	12	66.7	66.7
cleared	3.3	7	3	clear	5.5	5	2	80.0	71.4
agreed	4.6	6	1	agree	4.4	5	0	80.0	83.3
opened	4.9	6	2	open	5.7	4	3	80.0	66.7
played	4.7	6	6	play	5.6	4	5	75.0	66.7
talked	4.6	6	4	talk	5.6	4	8	75.0	66.7
hoped	4.1	5	9	hope	5.2	4	13	75.0	80.0
passed	4.9	6	6	pass	4.6	4	12	75.0	66.7
walked	5.0	6	4	walk	4.8	4	4	75.0	66.7
jumped	3.2	6	6	jump	3.3	4	6	80.0	66.7
pushed	4.1	6	5	push	3.8	4	8	75.0	66.7
filled	4.3	6	9	fill	3.7	4	15	75.0	66.7
caused	4.3	6	2	cause	5.0	5	1	75.0	83.3
saved	3.6	5	7	save	4.2	4	13	75.0	80.0
examined	3.4	8	2	examine	3.4	7	0	85.7	87.5
lifted	3.7	6	8	lift	3.8	4	9	66.7	66.7
baked	2.4	5	8	bake	1.7	4	16	75.0	80.0
reached	4.9	7	4	reach	4.5	5	7	75.0	71.4
named	4.0	5	4	name	5.6	4	9	75.0	80.0
pressed	3.6	7	2	press	4.9	5	4	80.0	71.4
chewed	1.8	6	0	chew	1.7	4	4	66.7	66.7
crawled	2.2	7	2	crawl	2.1	5	3	80.0	71.4
blamed	2.4	6	5	blame	3.6	5	5	80.0	83.3
chopped	2.4	7	5	chop	2.0	4	5	75.0	57.1
breathed	2.5	8	4	breathe	2.8	7	1	80.0	87.5
combed	1.6	6	1	comb	1.7	4	5	75.0	66.7
frowned	2.3	7	3	frown	1.8	5	5	80.0	71.4
prayed	2.2	6	4	pray	2.7	4	6	75.0	66.7
scrubbed	1.5	8	0	scrub	2.1	5	2	83.3	62.5
pulled	4.5	6	9	pull	4.2	4	13	75.0	66.7
sprayed	1.3	7	2	spray	2.4	5	2	80.0	71.4
touched	3.8	7	3	touch	4.6	5	5	75.0	71.4
splashed	1.6	8	1	splash	1.7	6	0	83.3	75.0
chased	2.1	6	4	chase	2.7	5	4	75.0	83.3
skated	−0.5	6	4	skate	1.3	5	3	66.7	83.3

APPENDIX A *(continued)*

Prime				Target				Phonological Overlap (% Phonemes)	Orthographic Overlap (% Letters)
Item	*Frequency*	*Length*	*N*	*Item*	*Frequency*	*Length*	*N*		
Mean	3.2	6.3	4.0		3.6	4.6	6.0	76.3	72.6
SD	1.3	0.8	2.4		1.4	0.8	4.5	4.6	7.8
Suffixed Irregular Verbs									
leapt	2.4	5	3	leap	2.6	4	7	50.0	80.0
dealt	3.1	5	1	deal	5.2	4	16	50.0	80.0
fled	2.8	4	8	flee	1.7	4	8	50.0	75.0
slept	3.5	5	2	sleep	4.8	5	5	60.0	60.0
kept	5.3	4	2	keep	5.9	4	9	50.0	50.0
sold	4.0	4	8	sell	4.0	4	11	50.0	50.0
meant	5.0	5	2	mean	6.0	4	9	50.0	80.0
heard	5.6	5	4	hear	5.2	4	15	66.7	80.0
built	4.8	5	3	build	4.3	5	2	75.0	80.0
bent	3.7	4	14	bend	3.1	4	10	75.0	75.0
crept	2.4	5	3	creep	2.1	5	3	60.0	60.0
swept	3.4	5	3	sweep	2.7	5	4	60.0	60.0
burnt	2.9	5	2	burn	3.3	4	7	75.0	80.0
sent	5.0	4	13	send	4.4	4	8	75.0	75.0
felt	6.0	4	7	feel	5.9	4	9	50.0	50.0
spent	4.9	5	3	spend	4.5	5	2	80.0	80.0
wept	2.2	4	5	weep	1.9	4	8	50.0	50.0
taught	4.2	6	2	teach	3.9	5	5	33.3	16.7
brought	5.5	7	2	bring	5.2	5	5	50.0	42.9
stood	5.4	5	3	stand	5.0	5	2	75.0	60.0
told	6.2	4	8	tell	6.1	4	12	50.0	50.0
caught	4.7	6	2	catch	4.2	5	6	33.3	50.0
lost	5.4	4	14	lose	4.4	4	12	50.0	75.0
dwelt	0.6	5	1	dwell	1.4	5	2	80.0	80.0
Mean	4.1	4.8	4.8		4.1	4.4	7.4	58.3	64.1
SD	1.4	0.8	4.0		1.4	0.5	4.0	13.9	16.8
Vowel-change Irregular Verbs									
tore	2.7	4	18	tear	2.9	4	16	66.7	25.0
wore	4.1	4	19	wear	4.2	4	14	66.7	25.0
gave	5.7	4	14	give	6.2	4	6	66.7	75.0
sang	2.9	4	15	sing	3.2	4	13	66.7	75.0
drew	4.1	4	4	draw	4.1	4	5	66.7	75.0
shook	4.2	5	3	shake	3.2	5	10	66.7	40.0

APPENDIX A (*continued*)

Prime				Target				Phonological Overlap (% Phonemes)	Orthographic Overlap (% Letters)
Item	*Frequency*	*Length*	*N*	*Item*	*Frequency*	*Length*	*N*		
spoke	4.7	5	5	speak	4.9	5	4	75.0	40.0
stung	1.2	5	4	sting	1.7	5	6	75.0	80.0
won	4.3	3	14	win	4.1	3	15	66.7	66.7
grew	4.3	4	5	grow	4.5	4	6	66.7	75.0
woke	3.2	4	7	wake	3.5	4	15	66.7	75.0
shone	2.7	5	6	shine	2.0	5	10	66.7	80.0
hung	4.0	4	8	hang	3.5	4	11	66.7	75.0
fell	4.7	4	13	fall	4.7	4	12	66.7	75.0
blew	3.1	4	5	blow	3.7	4	8	66.7	75.0
drove	4.2	5	4	drive	4.5	5	1	75.0	80.0
rang	3.6	4	14	ring	4.2	4	11	66.7	75.0
drank	3.5	5	5	drink	4.8	5	3	80.0	80.0
ran	4.7	3	16	run	5.4	3	14	66.7	66.7
stole	2.4	5	7	steal	2.5	5	4	75.0	40.0
found	6.2	5	8	find	6.3	4	11	60.0	20.0
chose	3.5	5	6	choose	4.2	6	1	66.7	50.0
sprang	2.5	6	2	spring	4.2	6	5	80.0	83.3
rode	2.7	4	13	ride	3.5	4	14	66.7	75.0
sank	2.6	4	14	sink	3.3	4	13	75.0	75.0
swam	2.0	4	11	swim	3.2	4	5	75.0	75.0
broke	4.2	5	2	break	4.7	5	6	75.0	40.0
fought	3.6	6	3	fight	4.6	5	8	66.7	16.7
swore	1.9	5	7	swear	2.7	5	4	75.0	40.0
threw	3.9	5	3	throw	3.9	5	2	66.7	80.0
stuck	3.8	5	3	stick	4.0	5	5	75.0	80.0
began	5.9	5	3	begin	4.8	5	2	75.0	80.0
flew	3.1	4	8	fly	3.9	3	6	66.7	50.0
wrote	4.9	5	1	write	4.8	5	4	66.7	80.0
swung	3.1	5	3	swing	3.4	5	6	75.0	80.0
held	5.4	4	9	hold	5.1	4	10	75.0	75.0
Mean	3.7	4.5	7.8		4.0	4.4	7.9	70.0	63.8
SD	1.1	0.7	5.1		1.0	0.7	4.5	4.9	20.5
Phonological									
fairy	2.4	5	4	fair	4.5	4	4	75.0	80.0
belly	2.8	5	7	bell	3.7	4	13	75.0	80.0
corner	4.6	6	1	corn	3.2	4	10	80.0	66.7

APPENDIX A *(continued)*

Prime				*Target*						
Item	*Frequency*	*Length*	*N*	*Item*	*Frequency*	*Length*	*N*	*Phonological Overlap (% Phonemes)*	*Orthographic Overlap (% Letters)*
master	3.9	6	7	mast	0.9	4	16	66.7	66.7
barn	2.3	4	12	bar	4.2	3	16	75.0	75.0
freak	1.6	5	3	free	5.3	4	3	75.0	60.0
keep	5.9	4	9	key	4.3	3	5	66.7	50.0
pitch	3.0	5	7	pit	2.6	3	18	66.7	60.0
bitter	3.6	6	8	bits	3.5	4	15	75.0	50.0
lawn	3.0	4	7	law	5.1	3	16	66.7	75.0
panel	3.0	5	1	pan	3.4	3	19	75.0	60.0
agent	3.8	5	0	age	5.5	3	9	40.0	60.0
plant	4.3	5	5	plan	4.6	4	3	80.0	80.0
seem	5.4	4	9	sea	5.1	3	10	66.7	50.0
blanket	2.8	7	0	blank	2.9	5	6	71.4	71.4
dear	4.8	4	15	dean	2.5	4	9	66.7	75.0
tank	3.0	4	12	rank	3.1	4	13	75.0	75.0
door	5.8	4	5	floor	5.1	5	2	50.0	40.0
match	4.0	5	7	mat	2.0	3	22	66.7	60.0
feet	5.4	4	8	fee	2.6	3	15	66.7	75.0
farm	4.2	4	6	far	6.2	3	17	75.0	75.0
early	5.8	5	1	earl	2.7	4	2	75.0	80.0
beef	2.8	4	6	bee	1.9	3	13	66.7	75.0
county	3.8	6	2	count	4.4	5	3	80.0	83.3
wink	1.2	4	11	sink	3.3	4	13	75.0	75.0
tent	3.6	4	15	ten	5.4	3	16	75.0	75.0
dollar	2.7	6	1	doll	2.9	4	11	60.0	66.7
army	4.7	4	2	arm	4.7	3	5	75.0	75.0
fancy	3.4	5	1	fan	2.4	3	16	60.0	60.0
party	5.9	5	6	part	6.2	4	17	80.0	80.0
start	5.4	5	4	star	4.0	4	7	80.0	80.0
home	6.2	4	10	some	7.6	4	7	66.7	75.0
pillow	2.6	6	2	pill	2.6	4	14	75.0	66.7
dragon	2.0	6	0	drag	2.9	4	7	66.7	66.7
Mean	3.8	4.9	5.7		3.9	3.7	10.9	70.3	68.9
SD	1.3	0.9	4.3		1.4	0.6	5.6	8.6	10.7
Semantic									
happy	4.9	5	2	sad	3.8	3	17	25.0	20.0
cat	3.7	3	22	dog	4.3	3	14	0.0	0.0

APPENDIX A (*continued*)

Prime				*Target*				*Phonological Overlap (% Phonemes)*	*Orthographic Overlap (% Letters)*
Item	*Frequency*	*Length*	*N*	*Item*	*Frequency*	*Length*	*N*		
grass	4.4	5	7	green	5.1	5	3	50.0	40.0
dinner	4.5	6	2	lunch	4.4	5	6	20.0	16.7
boots	3.4	5	11	shoes	4.2	5	5	0.0	40.0
skirt	3.0	5	1	dress	4.4	5	5	0.0	0.0
toe	2.3	3	17	heel	2.5	4	7	0.0	25.0
cry	3.9	3	6	laugh	4.0	5	0	0.0	0.0
salt	3.8	4	4	pepper	1.9	6	1	0.0	0.0
gold	4.5	4	9	silver	4.0	6	0	20.0	16.7
pear	0.9	4	15	apple	2.9	5	2	0.0	0.0
cow	3.1	3	23	horse	4.4	5	5	0.0	20.0
jam	2.6	3	12	toast	2.7	5	3	0.0	0.0
queen	3.9	5	1	king	4.5	4	9	25.0	0.0
cherry	1.8	6	2	grape	0.7	5	8	0.0	0.0
chair	4.7	5	2	table	5.3	5	4	0.0	0.0
peace	4.5	5	3	war	5.8	3	15	0.0	0.0
hot	4.9	3	17	cold	5.2	4	10	0.0	25.0
summer	4.8	6	2	winter	4.4	6	2	40.0	33.3
rule	4.2	4	5	law	5.1	3	16	33.3	0.0
couch	2.2	5	6	sofa	3.0	4	3	0.0	20.0
below	4.8	5	0	above	5.4	5	1	25.0	0.0
mad	3.9	3	22	anger	4.0	5	1	0.0	0.0
south	5.3	5	2	north	5.0	5	2	25.0	60.0
west	5.3	4	14	east	4.9	4	10	50.0	50.0
bread	4.3	5	6	butter	3.3	6	10	25.0	16.7
forest	4.2	6	0	trees	4.8	5	4	16.7	33.3
sugar	4.0	5	0	sweet	3.8	5	5	0.0	20.0
doctor	4.9	6	0	nurse	3.5	5	2	0.0	0.0
jacket	3.5	6	2	coat	4.0	4	9	20.0	0.0
smooth	3.6	6	0	rough	3.8	5	5	0.0	0.0
white	6.0	5	3	black	5.8	5	4	0.0	0.0
rose	4.6	4	14	red	5.2	3	12	33.3	25.0
sour	2.4	4	11	lemon	2.6	5	1	0.0	0.0
Mean	3.9	4.6	7.1		4.1	4.6	5.9	12.0	13.6
SD	1.1	1.0	7.1		1.1	0.9	4.8	16.1	17.0
"*−M + P + S*"									
scald	−0.8	5	4	scorch	−0.1	6	0	40.0	33.3

APPENDIX A (*continued*)

Prime				Target					
Item	*Frequency*	*Length*	*N*	*Item*	*Frequency*	*Length*	*N*	*Phonological Overlap (% Phonemes)*	*Orthographic Overlap (% Letters)*
scrape	1.6	6	1	scratch	2.4	7	0	60.0	57.1
screech	0.8	7	0	scream	2.6	6	1	80.0	57.1
shelve	−0.6	6	0	shelf	2.6	5	2	75.0	66.7
shrivel	−0.3	7	0	shrink	1.7	6	4	60.0	57.1
slither	0.1	7	0	slink	−0.8	5	6	50.0	42.9
ghost	3.0	5	0	ghoul	−0.4	5	0	50.0	60.0
groan	1.1	5	2	grumble	0.9	7	1	33.3	28.6
crinkle	−1.1	7	2	wrinkle	0.0	7	1	83.3	85.7
loathe	0.7	6	0	loath	−0.1	5	0	100.0	83.3
hotel	4.8	5	2	motel	1.9	5	4	80.0	80.0
nostril	0.6	7	0	nose	4.3	4	10	42.9	42.9
flutter	1.3	7	2	flurry	1.5	6	2	60.0	42.9
sneeze	0.3	6	0	snort	0.8	5	4	50.0	33.3
snarl	0.5	5	2	sneer	1.0	5	2	60.0	40.0
shovel	1.4	6	2	shove	1.4	5	4	75.0	83.3
shimmer	0.5	7	3	glimmer	0.7	7	2	80.0	71.4
converge	0.6	8	1	merge	1.2	5	3	50.0	50.0
plunge	2.0	6	0	plummet	−0.2	7	0	50.0	42.9
flood	2.8	5	2	float	2.8	5	2	75.0	60.0
bustle	1.3	6	2	hustle	0.2	6	3	75.0	83.3
devil	3.3	5	0	evil	4.0	4	0	75.0	80.0
ham	2.6	3	17	spam	4.7	4	7	50.0	50.0
freeze	2.2	6	2	frost	2.4	5	1	50.0	33.3
mohair	0.0	6	0	hair	5.3	4	5	75.0	66.7
placard	−0.6	7	0	card	3.8	4	12	66.7	57.1
elevator	2.1	8	0	escalator	0.3	9	0	62.5	11.1
Mean	1.1	6.1	1.6		1.7	5.5	2.8	63.3	55.6
SD	1.4	1.1	3.3		1.7	1.2	3.1	15.9	19.7

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