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An event-related potential study of cross-modal morphological and phonological priming

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ABSTRACT

The current work investigated whether differences in phonological overlap between the past- and present-tense forms of regular and irregular verbs can account for the graded neurophysiological effects of verb regularity observed in past-tense priming designs. Event-related potentials were recorded from 16 healthy participants who performed a lexical-decision task in which past-tense primes immediately preceded present-tense targets. To minimize intra-modal phonological priming effects, cross-modal presentation between auditory primes and visual targets was employed, and results were compared to a companion intra-modal auditory study (Justus, T., Larsen, J., de Mornay Davies, P., Swick, D. (2008). Interpreting dissociations between regular and irregular past-tense morphology: evidence from event-related potentials. *Cognitive, Affective, Behavioral Neuroscience*, *8*, 178–194.). For both regular and irregular verbs, faster response times and reduced N400 components were observed for present-tense forms when primed by the corresponding past-tense forms. Although behavioral facilitation was observed with a pseudo-past phonological control condition, neither this condition nor an orthographic-phonological control produced significant N400 priming effects. Instead, these two types of priming were associated with a post-lexical anterior negativity (PLAN). Results are discussed with regard to dual- and single-system theories of inflectional morphology, as well as intra- and cross-modal prelexical priming.

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1. Introduction

The English past tense has stimulated a long-standing debate on the nature of morphological representation, and by extension, the nature of mental representation more generally. All but approximately 180 verbs in the English language form both the simple past tense as well as the past participle by suffixation of /t/, /d/, or /Id/, depending on the final phoneme of the present-tense form, all of which are realized in writing by the suffix <-ed> (e.g., *look–looked*, *live–lived*, *need–needed*). These verbs constitute the class of regular verbs, which in turn are a subset of the weak verbs, or all the verbs that end with a dental stop consonant (/t/ or /d/) in the past tense. Weak irregular verbs are similar to regulars in that their past-tense forms end in a dental stop consonant, but they do not adhere to the pattern of the regular verbs (e.g., *spend–spent*, *hide–hid*, *put–put*). Strong verbs follow a pattern of vowel changes known as ablaut and do not typically end in a dental stop consonant in the past tense (e.g., *speak–spoke*, *sing–sang*, *fall–fell*). Finally, two verbs have suppletive past-tense forms (*am–was*, *go–went*). The weak irregular verbs, strong verbs, and suppletive verbs constitute the irregular verbs.

Dual-system theories argue for two separate processes of verb inflection, depending on whether a verb is regular or irregular. For the regular verbs, an algorithmic, rule-based process adds the suffix |-d| – which can be realized as one of the three allomorphs described above (/t/, /d/, or /Id/) – during past tense production, and a similar rule strips this suffix during past tense comprehension. In contrast, all irregular verbs, including weak irregulars and strong verbs, are considered to be exceptions to the rule and are stored in an associative lexical memory as full words (Pinker, 1999; Pinker and Ullman, 2002). The rule-based component of the dual system approach is grounded in the paradigm of generative linguistics in which symbols and propositions are manipulated and transformed during cognition.

Single-system theories argue that a single associative system, mapping relationships between form (phonology and orthography) and meaning (semantics), can model both regular and irregular inflectional morphology (Joanisse & Seidenberg, 1999; McClelland & Patterson, 2002). These models are a product of the connectionist paradigm that emerged in psychology beginning in the 1980s (Rumelhart & McClelland, 1986; Elman et al., 1996). In most such models, inflectional (and derivational) morphology is not specifically represented in the language system, but rather is an emergent property of language, reflecting quasi-regularities in the mapping between form and meaning (Seidenberg & Gonnerman, 2000; cf. Plaut, McClelland, Seidenberg, & Patterson, 1996 for a discussion of quasi-regularities in the mapping between phonology and orthography).

The past-tense debate is largely one of how to interpret the cognitive and neural dissociations between regular and irregular morphology. Such dissociations have been observed in data from acquisition (Brown, 1973; Kuczaj, 1977), psycholinguistics (Stanners, Neiser, Hernon, & Hall, 1979; Kempley & Morton, 1982; Napps, 1989; Sonnenstuhl, Eisenbeiss, & Clahsen, 1999; but see Fowler, Napps, & Feldman, 1985; Hanson & Wilkenfeld, 1985), neuropsychology (Ullman et al., 1997; Marslen-Wilson & Tyler, 1997; Tyler, de Mornay Davies, et al., 2002; Ullman et al., 2005; but see Faroqi-Shah, 2007), neuroimaging (Jaeger et al., 1996; Beretta et al., 2003; Sahin, Pinker, & Halgren, 2006; de Diego Balaguer et al., 2006), and electrophysiology (Gross et al., 1998; Morris & Holcomb, 2005; Münte, Say, Clahsen, Schiltz, & Kutas, 1999; Penke et al., 1997; Rodríguez-Fornells, Clahsen, Lleó, Zaake, & Münte, 2001; Rodríguez-Fornells, Münte, & Clahsen, 2002; Weyerts, Münte, Smid, & Heinze, 1996; Weyerts, Penke, Dohrn, Clahsen, & Münte, 1997). In general, most such dissociations, especially the double dissociation suggested by some of the neuropsychological cases, have tended to be interpreted as support for distinct cognitive mechanisms, reflecting a long-standing logic in cognitive neuropsychology that has been generalized to electrophysiology and neuroimaging.

The single-system rebuttal to such dissociations is to suggest that they are of a continuous nature, rather than being categorical (Joanisse & Seidenberg, 1999, 2005; Justus, Larsen, de Mornay Davies, & Swick, 2008; Justus et al., submitted for publication; Kielar, Joanisse, & Hare, 2008; McClelland & Patterson, 2002), and as such, they do not necessitate distinct cognitive mechanisms. Joanisse and Seidenberg (1999) developed a connectionist model of the past tense in which phonological units were interconnected with semantic units. They found that generating past tenses for novel words and regular verbs was more impaired following phonological damage to the model, whereas generating irregular pasts was more impaired following semantic damage. The argument that regular verb deficits arise from phonological deficits has also received some support from the neuropsychological literature (Bird, Lambon Ralph, Seidenberg, McClelland, & Patterson, 2003; Lambon Ralph, Braber, McClelland, & Patterson, 2005; Braber, Patterson, Ellis, & Lambon Ralph, 2005; but see Tyler, Randall, & Marslen-Wilson, 2002; Longworth, Marslen-Wilson, Randall, & Tyler, 2005; Ullman et al., 2005) as has the argument that irregular verb deficits arise from semantic deficits (Patterson, Lambon Ralph, Hodges, & McClelland, 2001; but see Miozzo, 2003; Tyler et al., 2004; Miozzo & Gordon, 2005).

1.1. Intra-modal morphological priming

We have previously reported the results of an event-related potential study of past tense priming using auditory primes and targets (Justus et al., 2008; cf. Justus et al., submitted for publication). The past tense served as the prime and the present tense served as the target in two conditions concerning past-tense morphology, one made up of regular verbs (e.g., *looked–look*) and the other of irregular verbs, which in turn were divided into a group of weak irregular verbs (e.g., *spent–spend*) and strong verbs (*spoke–speak*). Two comparison conditions were also included in an attempt to control for the differences in phonological and orthographic overlap between the present and past tenses of regular and irregular verbs. A pseudopast condition (e.g., *bead–bee*) included pairs of words that were semantically and morphologically unrelated, such that the prime word differed from the target by the addition of /t/ or /d/ in a manner phonologically (but not orthographically) consistent with the regular past tense. The inclusion of the pseudopast condition allows one to ask whether the system is specifically sensitive to phonological sequences that suggest affixation (cf. Taft & Forster, 1975). The orthophono condition (e.g., *barge–bar*) included pairs of words that were semantically and morphologically unrelated, such that the prime word differed from the target word by the addition of a single phoneme and one or two letters. Thus, unlike the pseudopast condition, the orthophono condition contained full orthographic overlap as well as phonological overlap between prime and target. This full orthographic overlap, in addition to phonological overlap, is also the case with regular verbs, with the exception of a few orthographic alternations (e.g., *tried–try*).

In addition to collecting behavioral data, the use of ERPs provided additional information regarding the time course and scalp distribution of the associated effects. Specifically, we examined an ERP component known as the N400, a negative wave that peaks at approximately 400 ms following the presentation of a potentially meaningful stimulus, such as a word or a picture (Kutas & Hillyard, 1980; Kutas & Federmeier, 2000). The size of the N400 has been shown to reflect the ease of semantic integration into the preceding context, with an inverse relationship between the size of the N400 and the predictability of the stimulus's occurrence given the context. Thus, a word or picture that has been primed is associated with a reduced N400 component.

Using the intra-modal auditory design, we obtained significant response time facilitation for all four groups of stimuli, and a corresponding reduction in the size of the early portion of the N400 component. The regular and irregular priming effects were not significantly different from each other as measured by the response time and early N400 data. The effects for the two verb classes were larger than those of the pseudopast and orthophono conditions, numerically in the case of the behavioral data and significantly in the case of the early N400 data. During the later portion of the N400 component, priming effects only remained significant for the two verb classes. Further, the priming effect for the irregular verbs was stronger than that for the regular verbs, with the difference being driven by the strong verbs.

Because we observed a continuous or graded dissociation between regular and irregular verbs, which was not easily accounted for in terms of phonological and orthographic overlap, we interpreted these results as partially consistent with the single-system, connectionist notion that regular and irregular verbs fall on a continuum of regularity and a concomitant continuum of dependence on semantic representations (Joanisse & Seidenberg, 1999; McClelland & Patterson, 2002; cf. Baayen & Moscoco del Prado Martín, 2005). Specifically, stronger semantic links between irregular past- and present-tense forms are proposed to result from the less predictable phonological relationship between the two, in contrast to the perfectly predictable phonological relationship between regular past- and present-tense forms.

1.2. Intra-modal phonological priming

The facilitating phonological priming effects observed by Justus et al. (2008) were also of interest in their own right, because similar controls in previous past tense studies have not yielded significant effects and sometimes showed a trend towards inhibition (Longworth, Keenan, Barker, Marslen-Wilson, Tyler, 2005; Tyler, de Mornay Davies, et al., 2002, Tyler et al., 2004).

A closer inspection of the phonological priming literature using intra-modal auditory presentation also reveals quite variable effects for initial overlap. The choice of task in particular plays a major role in whether effects are observed at all, and if so, whether they are facilitatory or inhibitory (cf. Slowiaczek & Pisoni, 1986; Slowiaczek, Nusbaum, & Pisoni, 1987). Some authors have argued for a combination of prelexical facilitation and lexical inhibition, given that the facilitatory effects of one-phoneme overlap (e.g., *smoke–still*) tend to change to inhibition with two- or three-phoneme overlap (e.g., *stiff–still*, Slowiaczek & Hamburger, 1992; cf. Radeau, Morais, & Dewier, 1989; Radeau, Morais, & Segui, 1995; Monsell & Hirsh, 1998; Dufour & Peereman, 2003). In support of this idea, Slowiaczek and Hamburger (1992) showed that the facilitatory effect could be produced in a shadowing task with both word and non-word primes, but the inhibitory effect was specific to word primes. Later work, in which the proportion of related items and the prime–target interstimulus-interval (ISI) were manipulated, suggested that the proposed prelexical facilitation may be due to response biases and other strategic effects (Goldinger, Luce, Pisoni, & Marcario, 1992; Hamburger & Slowiaczek, 1996, 1999; Goldinger, 1999). Biases have been argued to play a role in the proposed lexical inhibition as well (Pitt & Shoaf, 2002). The small consensus available on the issue would suggest that all three effects – prelexical facilitation, lexical inhibition, and strategic processes – may operate simultaneously in designs employing initial overlap (cf. McQueen & Sereno, 2005). Briefly, the evidence seems much clearer that facilitation occurs for *final* syllable overlap in intra-modal designs regardless of the lexical status of the prime, and that automatic prelexical facilitation as well as strategic processes contribute to this effect (Slowiaczek, McQueen, Soltano, & Lynch, 2000; Norris, McQueen, & Cutler, 2002).

With regard to the electrophysiology of auditory intra-modal phonological priming, N400 reductions have been reported with final syllable overlap (Praamstra & Stegeman, 1993; Praamstra, Meyer, & Levelt, 1994; Dumay et al., 2001; Perrin & García-Larrea, 2003), complementing earlier work in the visual modality showing N400 reductions for a word that rhymed with the preceding word (Sanquist, Rohrbaugh, Syndulko, & Lindsley, 1980), even when rhyming words were orthographically dissimilar (Rugg, 1984a, 1984b; Rugg & Barrett, 1987; Kramer & Donchin, 1987). Some authors have argued that the N400 is modulated by phonological repetition only when it is task-relevant, as in a rhyme judgment task (Perrin & García-Larrea, 2003), despite prior observations of the effect with shadowing (Dumay et al., 2001) and with lexical decision (Praamstra & Stegeman, 1993; Praamstra et al., 1994). In their Dutch study, Praamstra et al. (1994) also tested the effect of overlap of the initial two phonemes (e.g., *kost–korf*), and despite not finding a significant behavioral effect in this condition, they did find significant N400 reductions related to initial overlap, as in our intra-modal study (Justus et al., 2008).

Returning to the past tense, the three potential effects of initial phonological overlap in intra-modal designs – prelexical facilitation, lexical inhibition, and strategic processes – are relevant not only for the interpretation of our phonological control conditions, but of the past-tense conditions themselves, which also share word-initial overlap. Further, regular verbs and weak irregular verbs contain more word-initial overlap (e.g., *looked–look*; *spent–spend*) than do strong verbs (e.g., *spoke–speak*). These three classes also differ in the degree of divergence on the final segment. Thus, lexical inhibition based on larger degrees of initial overlap, along with a lack of overlap for word offset, might provide an explanation for why regular verbs, along with weak irregular verbs, do not prime as strongly as do strong verbs in the intra-modal design. Given this, we considered the example of another branch of the morphological priming literature employing cross-modal presentation.

1.3. Cross-modal morphological and phonological priming

Cross-modal priming designs were first employed in the context of semantic priming (Swinney, Onifer, Prather, & Hirshkowitz, 1979) and later were instrumental in documenting the lexical activation of cohorts of words sharing initial phonemes (e.g., general, generous) by presenting visual targets at various stimulus-onset asynchronies (SOA) relative to the presentation of an auditory prime (Marslen-Wilson & Zwitserlood, 1989; Zwitserlood, 1989).

Within the morphological literature, an auditory-to-visual cross-modal priming design has been used both in the context of derivational morphology (Marslen-Wilson, Tyler, Waksler, & Older, 1994; Gonnerman, Seidenberg, & Andersen, 2007) and inflectional morphology (Allen & Badecker, 2002; Marslen-Wilson, Hare, & Older, 1993, as cited by Allen & Badecker, 2002; Marslen-Wilson & Tyler, 1998; Basnight-Brown, Chen, Hua, Kostić, & Feldman, 2007; Kielar et al., 2008, Exp. 2). The initial argument for the use of cross-modal presentation in these designs was to eliminate prelexical, modality-specific components of auditory priming – including the priming of acoustic elements, phonemes, and syllables – and instead to limit the effects to the lexical entry (Marslen-Wilson et al., 1994).

In hindsight, this assumption may not have been warranted, given a large body of evidence for prelexical cross-modal interactions, in accordance with the bimodal interactive activation model (Grainger & Ferrand, 1996). Some of the evidence for bimodal interactive activation concerns the modulation of intra-modal visual tasks by phonological factors (Meyer, Schvaneveldt, & Ruddy, 1974; Ferrand & Grainger, 1992; Grainger & Ferrand, 1994, 1996; Carreiras, Ferrand, Grainger, & Perea, 2005) and the modulation of intra-modal auditory tasks by orthographic factors (Seidenberg & Tanenhaus, 1979; Hillinger, 1980; Jakimik, Cole, & Rudnicky, 1985; Ziegler & Ferrand, 1998; Ziegler, Muneaux, & Grainger, 2003; Slowiaczek, Soltano, Wieting, & Bishop, 2003; Miller & Swick, 2003; Chéreau, Gaskell, & Dumay, 2007; Pattamadilok, Morais, Ventura, & Kolinsky, 2007; Pattamadilok, Perre, Dufau, & Ziegler, 2009).

Regarding prelexical components to cross-modal priming, the evidence is more equivocal. Dumay et al. (2001) did not find priming between visual pseudoword primes and auditory targets with final-syllable overlap (e.g., **LURAGE–tirage*).[1] However, Grainger, Diependaele, Spinelli, Ferrand, and Farioli (2003) did observe an effect of visually presented non-word pseudo-homophone primes on auditory word targets (e.g., **FROIE–froid*), suggesting an automatic phonological recoding of the orthographic prime. Slowiaczek and Hamburger (1992) also included a cross-modal priming manipulation and found that presenting primes visually with auditory targets tended to eliminate the facilitation effect for one-phoneme overlap (e.g., *SMOKE–still*) that they observed with auditory primes, consistent with the argument that this effect is prelexical. However, they continued to observe interference effects for three-phoneme overlap (e.g., *STIFF–still*) regardless of prime modality, consistent with the argument that this effect is lexical.

In the reverse direction, facilitatory cross-modal priming has been observed between auditory primes and visual targets when the prime represents the initial syllable of the target (e.g., *ver-VERTIGE*; Spinelli, Segui, & Radeau, 2001). However, non-significant inhibitory trends have been observed when the target represents the initial syllable(s) of the prime (*vendredi-VENDRE*; Longtin, Segui, & Hallé, 2003) and when both words are bisyllabic with a shared initial syllable (e.g., *verger-VERTIGE*; Spinelli et al., 2001). Flat effects have been observed when the prime represents the final syllable of the target (e.g., *tige–VERTIGE*; Spinelli et al., 2001; cf. Radeau, Segui, & Morais, 1994 as cited by Radeau et al., 1995). Because such effects are observed only for initial-syllable overlap, they are likely lexical, reflecting the activation and inhibition of a word cohort by the onset of the auditory prime, and do not necessarily represent a cross-modal prelexical priming effect between phonemes and graphemes.

Thus, there is some suggestion in the literature that using a cross-modal priming technique eliminates prelexical components to priming, despite the predictions of the bimodal interactive activation model (which nonetheless receives support in other experimental designs). Lexical effects, perhaps both facilitatory and inhibitory, seem to persist, as presumably do effects of bias and strategy, although this last issue has not been debated as thoroughly in the cross-modal literature. Given that the phonological priming effects observed in the Justus et al. (2008) study were facilitatory, we predicted that they were prelexical in nature and might be eliminated using the cross-modal design.

[1] In this paper, visual stimuli will be indicated by capital letters and auditory stimuli by lower-case letters.

1.4. The role of stimulus-onset asynchrony and interstimulus interval

The current study as well as its intra-modal predecessor employed a relatively long stimulus-onset asynchrony (SOA) between prime and target of 1400 ms, which resulted in an average interstimulus interval (ISI) of 870 ms. It is important to keep the relatively long ISI in mind first given that the automatic spread of activation and inhibition across phonological, orthographic, morphological, and semantic units is a dynamic process, as demonstrated by morphological priming studies that have systematically manipulated the ISI (e.g., Rastle, Davis, Marslen-Wilson, & Tyler, 2000). Further, whereas a shorter ISI is typically regarded as reflecting automatic spreading activation, a longer ISI permits a greater degree of expectancy-based priming as well as post-lexical processes (Neely, 1991). Thus, the current experiment permits the introduction of strategic effects.

Cross-modal designs using auditory primes and visual targets have often used an ISI of 0, with the visual target appearing at prime offset (Marslen-Wilson et al., 1994; Gonnerman et al., 2007; Allen & Badecker, 2002; Basnight-Brown et al., 2007). A short ISI was considered undesirable for an ERP study, given that we wished to ensure that the ERPs to the prime words would not overlap with the ERPs to the target words, allowing us to conduct a pure analysis of the latter. One cross-modal study that systematically manipulated ISI was that of Kielar et al. (2008, Exp. 2), who included two different ISIs (0 and 500 ms) between auditory primes and visual targets. The patterns of morphological and phonological priming were largely similar across the two conditions, although purely semantically related words demonstrated significant priming only with the longer ISI. Thus, the current experiment may also permit greater degrees of semantic priming than would be the case with a short-ISI study.

1.5. The present study

The present study sought to replicate our previous experiment in which overt past-tense primes immediately preceded present-tense targets, but with cross-modal presentation rather than auditory intra-modal presentation. Specifically, the prime was auditory and the target visual. As the preceding review suggests, a variety of phonological priming effects operate prelexically, lexically, and through strategic biases in the intra-modal design. Prelexical effects in particular appear to be reduced, but perhaps not eliminated, with cross-modal presentation. Regular and irregular verbs differ in the degree of phonological onset overlap between the present- and past-tense forms. Thus, by reducing this aspect of the observed behavioral and ERP effects, the present study tested whether our previously observed continuous dissociation between regular and irregular verbs would replicate. A replication of the continuous regular–irregular dissociation would be consistent with the conclusion of Justus et al. (2008) that the observed differences were not due to phonological differences between regular and irregular verbs. If on the other hand, the dissociation diminished with cross-modal presentation, this would suggest that phonological differences did in fact play a larger role in the intra-modal design than was previously acknowledged.

In addition to quantifying the N400 priming effect, we measured a second ERP component known as the late positive component (LPC), which is more prominent to visually presented words. The LPC follows the N400 and is thought to reflect stimulus categorization and decision processes. Although of less interest in most language studies than the N400, the LPC has been widely studied in explicit and implicit memory tasks (e.g., Swick & Knight, 1997). The LPC becomes greater in amplitude (more positive-going) after immediate stimulus repetition or repetition at longer lags (Karayanidis, Andrews, Ward, & McConaghy, 1991; Nagy & Rugg, 1989), but is less often influenced by semantic priming (Holcomb & Neville, 1990).

2. Method

2.1. Participants

Sixteen healthy young adults participated in the experiment (aged 24 ± 3 years; education 15 ± 2 years; 9 women, 7 men). All participants were right handed and native speakers of U.S. English. None had participated in the intra-modal auditory experiment reported by Justus et al. (2008).

2.2. Procedure

Following an informed consent procedure and application of the recording electrodes, participants were seated in a sound-attenuated booth. Each trial of the experiment began with fixation for 1500 ms, followed by the auditory prime. 1400 ms after the onset of the prime (an average ISI of 870 ms, given mean prime length of 530 ms), the visual target was presented at approximately 3 degrees of visual angle in the center of the visual field for 200 ms in lower-case. Participants were instructed to identify quickly and accurately whether each written item was a real word or a nonword, and indicated each response by pressing one of two buttons with the left or right thumb. Response mapping was counterbalanced between participants.

2.3. Design and selection of stimuli

The 1200 stimulus items of Justus et al. (2008) were used, resulting in 600 prime–target pairs with a 4 (regular, irregular, pseudopast, orthophono) by 3 (primed, unprimed, nonword) design and 50 trials per cell (Table 1). All cells consisted of 46 monosyllabic prime–target pairs and 4 bisyllabic prime–target pairs. All of the 600 primes and 400 of the 600 targets were real words, selected with the aid of the CELEX Lexical Database (Baayen, Piepenbrock, & Gulikers, 1995). The remaining 200 targets were selected using the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002).

One design constraint that was adopted given the use of ERP data (requiring at least 50 items per cell), the desire to avoid repetition effects on the N400 (observed even for extremely long lags; Nagy & Rugg, 1989; Bentin & Peled, 1990), and the small number of available stimuli in some conditions (especially the pseudopast condition) was the decision to use a between-item design. Accordingly, extreme care was taken to balance the items used in the primed and unprimed conditions – as well as the prime words in the nonword condition – on factors such as lemma frequency, syllabicity, word class, number of phonemes, number of letters, and in the case of irregular verbs, the type of irregularity. This was done simultaneously with the constraint to balance the same factors as closely as possible between the regular, irregular, pseudopast, and orthophono conditions. Further constraints on the selection of stimulus items for each Word Type were as follows.

Regular verbs: 150 regular verbs were selected and divided between the primed, unprimed, and nonword conditions. All were the /t/ or /d/ rather than the /Id/ allomorph, in order to control for syllabicity with the other conditions. Regular past tenses that shared pronunciations with other words were avoided (e.g., *packed–PACK*, cf. *pact*, or *missed–MISS*, cf. *mist*).

Irregular verbs: 150 of the ~180 irregular English verbs were selected. Modal forms (e.g., *could–CAN*, *would–WILL*) were avoided, as were words that are typically regularized in U.S. English (e.g., *learnt–LEARN*, *spilt–SPILL*). The chosen items were divided into primed, unprimed, and nonword conditions as

Table 1
Cross-modal immediate-priming design with lexical decision.

Word type	Priming	Prime (Aud.)	Target (Vis.)	Target Freq.[a]
Regular verbs ($n = 150$)	Primed	*looked*	*LOOK*	1.94 ± 0.4
	Unprimed	*worked*	*SEEM*	1.94 ± 0.4
	Nonword	*asked*	**TARB*	
Irregular verbs ($n = 150$)	Primed	*spoke*	*SPEAK*	1.98 ± 0.8
	Unprimed	*bound*	*WAKE*	1.98 ± 0.8
	Nonword	*took*	**PLINN*	
Pseudopast ($n = 150$)	Primed	*bead*	*BEE*	1.61 ± 1.1
	Unprimed	*bulb*	*PIE*	1.59 ± 1.1
	Nonword	*deer*	**CLEETH*	
Orthophono ($n = 150$)	Primed	*barge*	*BAR*	1.29 ± 0.9
	Unprimed	*bribe*	*TEA*	1.21 ± 0.8
	Nonword	*pouch*	**GWAL*	

[a] Log lemma frequency per million ± s.d.

follows. First, to avoid repetition priming, the 26 no-change irregulars (e.g., *put*) were used as primes only in the nonword condition. The remaining 45 weak irregulars in the set (e.g., *spent–SPEND*) were divided between the primed ($n = 23$) and unprimed ($n = 22$) conditions. The rest of the words in the three conditions ($n = 27$, 28, and 24) were strong verbs (e.g., *spoke–SPEAK*), or, in two cases, suppletive verbs (*was–IS, went–GO*). Care was taken to distribute the subordinate families of irregular verbs as evenly as possible through the three conditions, given these constraints.

Pseudopast: 50 pairs of semantically unrelated words were selected in which the prime word differed from the target word by the addition of /t/ or /d/, in a manner phonologically consistent with the regular past tense (e.g., *bead–BEE*). Potential stimuli overlapping with items in the verb conditions (e.g., *field–FEEL, bide–BUY*) or sharing pronunciations with regular verbs were avoided. Given the small number of appropriate monosyllabic pairs available in English, these 50 pseudopasts were all used in the primed condition. The items in the unprimed and nonword conditions were designed by choosing items of the same word class, frequency, and to the extent possible, number of phonemes and letters as in the primed condition.

Orthophono: 50 pairs of semantically unrelated words were selected in which the prime word differed from the target word by the addition of a single phoneme and one or two letters (e.g., *barge–BAR*). Unlike the pseudopast condition, this addition was not phonologically consistent with any regular past tense form, and spelling of the shorter target word was completely contained within the spelling of the longer prime word. These 50 orthophono prime–target pairs were all used in the primed condition. Like the pseudopast condition, the items in the unprimed and nonword conditions were designed by choosing items of the same word class, frequency, and number of phonemes and letters as in the primed condition.

The entire stimulus set may be viewed in the Appendix of Justus et al. (2008).

2.4. Stimulus recording

Sound files for the prime words were digitally recorded in a sound-attenuated booth by a native speaker of U.S. English, who was naïve to the purpose of the experiment. The speaker was coached in pronouncing the words and nonwords correctly, and in delivering all items clearly and with a consistent intonation, sound level, and speed. A pseudorandom recording order was created to ensure that no changes in speech over the course of the recording session would correlate with experimental factors.

Recordings were later filtered of white noise and edited into individual sound files, which were further normalized for sound level. Analyses of sound file lengths confirmed that these were properly balanced.

2.5. EEG recording

Electroencephalographic (EEG) activity was recorded using 26 electrodes embedded in an electrode cap. These electrodes consisted of the 19 electrodes of the International 10–20 system (Jasper, 1958) plus 7 additional electrodes at positions AF3/4, FC5/6, CP5/6, and POz. Four external electrodes recorded the left mastoid, right mastoid, left-horizontal EOG, and left-vertical EOG. EEG was recorded with reference to the left mastoid, and later re-referenced to the average of the two mastoids. Signals were amplified ($\times$20,000), filtered (1–80 Hz), and digitized at a sampling rate of 256 Hz (SA Instrumentation). Eye-blinks that were uncontaminated by additional artifacts were corrected using an adaptive filtering algorithm.

Based on visual inspection of the averaged data, mean amplitudes were calculated for the target words across two time windows of 200–400 ms and 400–600 ms following word onset, relative to a 100-ms window preceding word onset. The 200–400 ms window was chosen because it centered on the N400 component. It was clear that additional differences were emerging following 400 ms, and thus a second window of equal size, from 400 to 600 ms, was chosen to examine these later effects centered on the late positive component (LPC). These two time windows are shifted 100 ms earlier relative to those used by Justus et al. (2008). This is consistent with the expected and observed differences in the onset latency and duration of the N400 priming effect in response to auditory and visual words (Holcomb & Neville, 1990). No main effects of electrode are reported. Interactions involving electrode are reported with uncorrected F-values and degrees of freedom, and with Greenhouse–Geisser corrected p-values.

Topographic maps showing the distribution of the N400 effect for the target words were created by calculating voltage differences between the unprimed and primed conditions at each electrode and interpolating voltage differences for the rest of the scalp using a spherical spline mapping method (Perrin, Pernier, Bertrand, & Echallier, 1989).

3. Results

3.1. Behavioral data

An ANOVA of the response times for correct lexical decisions revealed main effects of Word Type [$F(3,45) = 20.9$, $p < 0.001$] and Priming $F(1,15) = 9.9$, $p = 0.007$]. Participants tended to be faster overall in responding to the two verb conditions, and slower for the two phonological conditions, independently of the priming manipulation. They were also faster in responding to primed words (Fig. 1A). The interaction between Word Type and Priming was not significant [$F(3,45) = 1.4$, $p = 0.26$]. Nevertheless, we performed a series of planned comparisons, given that a major interest a priori was the relative sizes of the four priming effects. Significant, positive priming was found for three of the four Word Types individually [regular: 45 ms, $F(1,15) = 17.9$, $p < 0.001$; irregular: 34 ms, $F(1,15) = 13.0$, $p = 0.003$; pseudopast: 27 ms, $F(1,15) = 5.5$, $p = 0.03$; orthophono: 11 ms, $F(1,15) = 0.3$, $p = 0.59$].

A second analysis explored the effect of the degree of irregularity, within the irregular word set (Fig. 1B). Significant positive priming was observed for the strong verbs [59 ms, $F(1,15) = 15.4$, $p < 0.001$] but not for the weak irregular verbs [21 ms, $F(1,15) = 1.4$, $p = 0.26$]. However, there was not a significant difference in the size of the priming effect between the strong verbs and the weak irregular verbs [$F(1,15) = 1.9$, $p = 0.19$], nor between each of these groups and the regular verbs (each $p > 0.20$).

3.2. ERP data – target words

Central-parietal region of interest. Preliminary analyses using two time windows (200–400 ms and 400–600 ms) overall 26 scalp electrodes revealed an N400 priming effect that was centered over central-posterior electrodes. Accordingly, we first chose a 9-electrode region of interest (Cz/Pz/POz/C3/C4/CP5/CP6/P3/P4) to examine the relative sizes and durations of the N400 effect across the four conditions (Fig. 2A). A pair of $4 \times 2 \times 9$ ANOVA were performed using the variables of Word Type, Priming, and Electrode for this ROI, one for each time window.

The N400 component was measured with a 200–400 ms window. During this window, there were robust main effects of Word Type [$F(3,45) = 9.3$, $p < 0.001$] and Priming [$F(1,15) = 9.3$, $p = 0.008$] as well as an interaction between these variables [$F(3,45) = 4.9$, $p = 0.005$]. Significant N400 reductions were observed for primed regular [$F(1,15) = 21.6$, $p < 0.001$] and irregular verbs [$F(1,15) = 11.0$, $p = 0.005$], but not for the pseudopast ($p = 0.66$) or orthophono conditions ($p = 0.78$). Planned comparisons revealed that regular and irregular priming effects were statistically indistinguishable during this time window ($p = 0.57$). However, both verb classes reliably primed more strongly than did each semantically unrelated control (four interactions, each $p < 0.02$). Priming in the pseudopast and orthophono conditions did not differ ($p = 0.93$).

In an analysis that divided irregulars into strong and weak irregular verbs (Fig. 2B), a significant priming effect was found for strong verbs [$F(1,15) = 24.1$, $p < 0.001$], but not for weak irregular verbs [$F(1,15) = 2.2$, $p = 0.16$]. These two effects were not significantly different between 200 and 400 ms ($p = 0.26$). [2]

The late positive component (LPC) was the predominant feature during a 400–600 ms window. During this window, there was a significant effect of Word Type [$F(3,45) = 17.0$, $p < 0.001$] but not of

[2] These two analyses were also repeated using a narrower window of 284–384 ms, which was centered on the peak amplitude of the N400 priming effect across the two verb conditions (334 ms). The patterns of statistical significance were identical regardless of whether the 200–400 ms window or the 284–384 ms window was used.

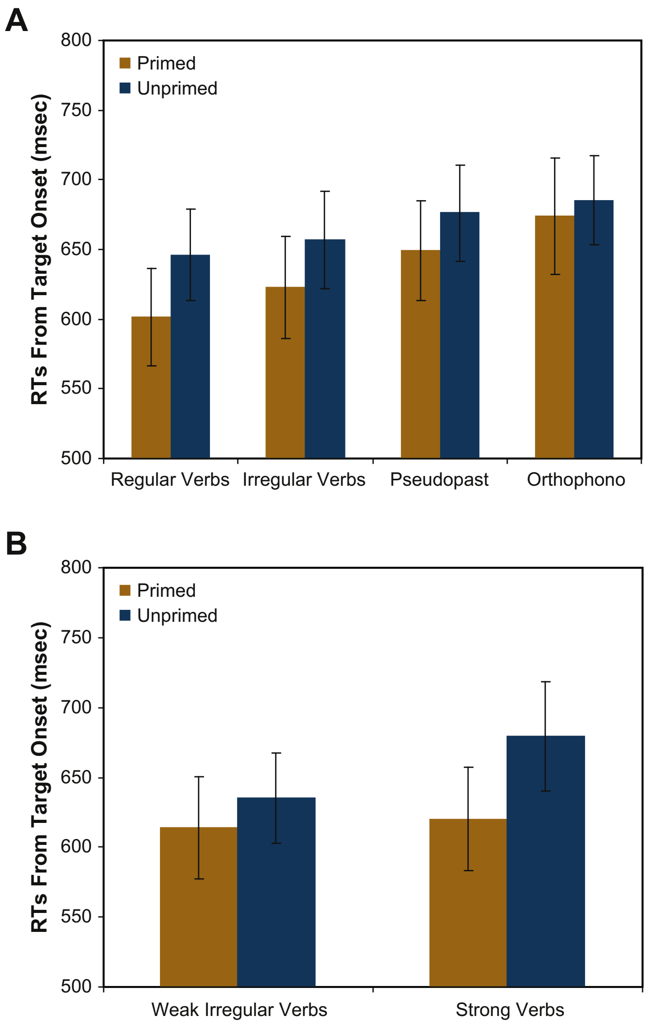

Fig. 1. Behavioral data. Mean response times (RTs) for correct lexical decisions (A) as a function of word type (regular verbs, irregular verbs, pseudopast, and orthophono) and priming, and (B) for the irregular verbs alone, separated into weak irregular verbs and strong verbs. Error bars represent standard errors.

Priming [$F(1,15) = 1.9$, $p = 0.19$]. Further, there was a significant Word Type by Priming interaction [$F(3,45) = 5.1$, $p = 0.004$]. Significant priming effects were observed for the pseudopast [$F(1,15) = 7.2$, $p = 0.02$] and orthophono conditions [$F(1,15) = 6.7$, $p = 0.02$], but not for the regular ($p = 0.80$) or irregular verbs ($p = 0.24$). Note that the direction of the effect is opposite of that of N400 reduction; the primed pseudopast and orthophono items are *more* negative (less positive) compared to the unprimed items. Planned comparisons revealed that priming in the pseudopast and orthophono conditions did not differ ($p = 0.96$). However, each of these semantically unrelated controls was significantly different from each verb class (four interactions, each $p < 0.04$). The non-significant priming effects observed in the regular and irregular verb conditions were statistically indistinguishable from each other [$F(1,15) = 1.0$, $p = 0.33$].

When comparing the strong and weak irregular verbs during this window, significant priming was again found for strong verbs [$F(1,15) = 33.1$, $p < 0.001$], but not for weak irregular verbs [$F(1,15) = 0.15$,

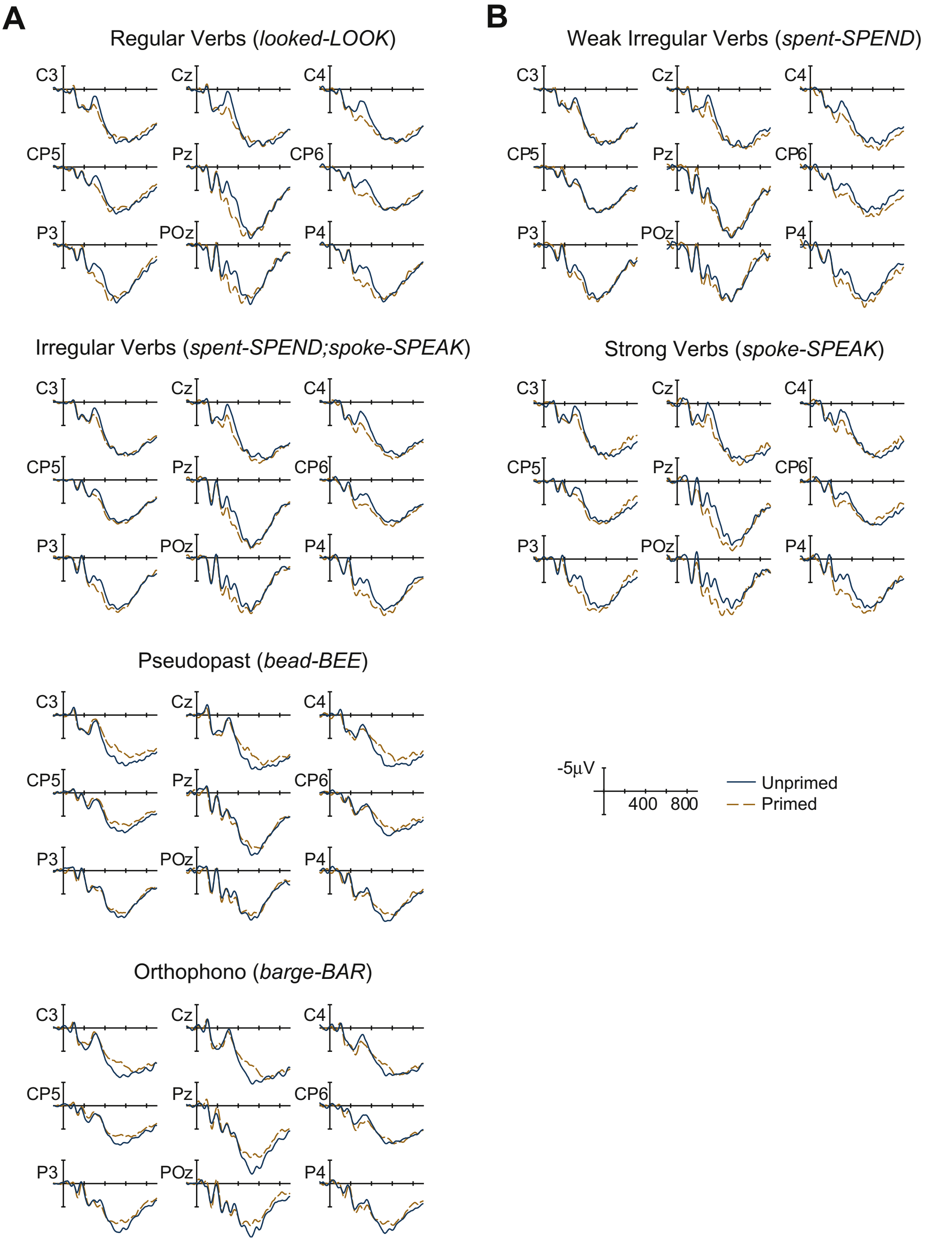

Fig. 2. ERPs to target words within the nine-electrode region of interest, demonstrating the N400 and LPC (A) as a function of word type (regular verbs, irregular verbs, pseudopast, and orthophono) and priming, and (B) for the irregular verbs alone, separated into weak irregular verbs and strong verbs.

$p = 0.70$]. Further, there was greater priming for strong relative to weak irregular verbs [$F(1,15) = 6.9$, $p = 0.02$]. The numeric difference between the irregulars as a group compared with the regulars seems to be driven primarily by the strong verbs; the priming effect for the strong verbs was significantly larger than that for the regular verbs [$F(1,15) = 15.5$, $p < 0.001$] but the priming effect for the weak irregular verbs was not ($p = 0.79$).

Scalp distributions. The above region of interest analysis limited the data to the central-parietal electrodes, where the N400 is most readily observed. This was done to maximize sensitivity for the detection of differences in the amplitude of the N400 priming effect as a function of Word Type. This approach may result in a failure to observe differences in the scalp distribution of the effect across Word Types. Therefore, the priming effect sizes at all scalp electrodes were used to generate topographic maps at both the 200–400 ms and 400–600 ms windows for both the four Word Types (Fig. 3A) and for the weak irregular/strong verb split (Fig. 3B).

The figures provide some suggestion that the topography of the N400 priming effect observed for the regular and irregular verbs differed from that of the reverse-direction pseudopast/orthophono effects observed during the later LPC interval. To fully explore this possibility, we performed a final pair of analyses using 16 electrodes, grouped into four quadrants (anterior left: FP1/F3/F7/FC5; anterior right: FP2/F4/F8/FC6; posterior left: O1/P3/T5/CP5; posterior right: O2/P4/T6/CP6). We conducted an additional pair of $4 \times 2 \times 2 \times 2$ ANOVA for the two time windows, with Word Type, Priming, Anterior/Posterior, and Left/Right as factors. Only the interactions of interest involving Priming and one of the topographic variables are reported.

During the 200–400 ms window, significant interactions between Priming and Anterior/Posterior [$F(1,15) = 10.0$, $p = 0.006$] and between Priming and Left/Right [$F(1,15) = 19.9$, $p < 0.001$] confirmed the visual impression that the N400 priming effect was larger over the posterior electrodes and the right hemisphere. The four-way interaction between all variables approached significance [$F(3,13) = 2.6$, $p = 0.085$], perhaps reflecting the larger differences between the regular–irregular priming effects and the non-significant pseudopast/orthophono priming effects in the posterior right quadrant (cf. Fig. 3A).

During the 400–600 ms window, the interaction between Priming and Anterior/Posterior was again significant [$F(1,15) = 5.7$, $p = 0.03$], with greater priming over the anterior electrodes. The four-way interaction between all variables reached significance [$F(3,13) = 3.3$, $p = 0.047$]. Four subsequent analyses tested the interaction between Word Type and Priming separately for the four quadrants: anterior left [$F(3,13) = 1.5$, $p = 0.24$], anterior right [$F(3,13) = 3.8$, $p = 0.03$], posterior left [$F(3,13) = 2.9$, $p = 0.05$], and posterior right [$F(3,13) = 3.9$, $p = 0.02$]. Examination of the priming effects across each Word Type and quadrant suggests that the four-way interaction results from the reverse-direction pseudopast/orthophono priming effects, which are distinguishable from the regular–irregular priming effects during this time window for all quadrants except for the anterior left (cf. Fig. 3A).

4. Discussion

4.1. Summary of results

Hearing the past-tense form of both regular and irregular English verbs facilitates a lexical decision to the corresponding, visually presented, present-tense form (e.g., *looked–LOOK* or *spoke–SPEAK*). This behavioral facilitation is accompanied by a reduction in the N400 component, with a right-sided asymmetry, that occurs in response to the visually presented target word. The sizes of the behavioral and N400 priming effects for primed regular and irregular words were comparable when irregulars were considered as a single group. However, a division of the irregular verbs into weak irregular (e.g., *spent–SPEND*) and strong verbs (e.g, *spoke–SPEAK*) demonstrated that the behavioral effects were numerically larger and the ERP priming effects were significantly larger (during the 400–600 ms window) for strong verbs compared to weak irregulars.

Two phonological and orthographic control conditions were also employed. The pseudopast condition, in which the prime word differed from the target by the addition of /t/ or /d/ in a manner phonologically (but not orthographically) consistent with the regular past tense (e.g, *bead–BEE*), resulted in a smaller but significant behavioral facilitation for the target word. The orthophono condition, in which the prime word differed from the target word by the addition of a single phoneme and one or two letters (e.g., *barge–BAR*), resulted in a non-significant facilitatory trend. In contrast to the behavioral results, no significant facilitation effect was observed for these conditions in the N400 region of interest during the 200–400 ms window. Much more compelling were the reverse-direction effects on the late positive component observed between 400 and 600 ms, such that the *primed* waveforms were more negative than were the unprimed waveforms. The time course and scalp

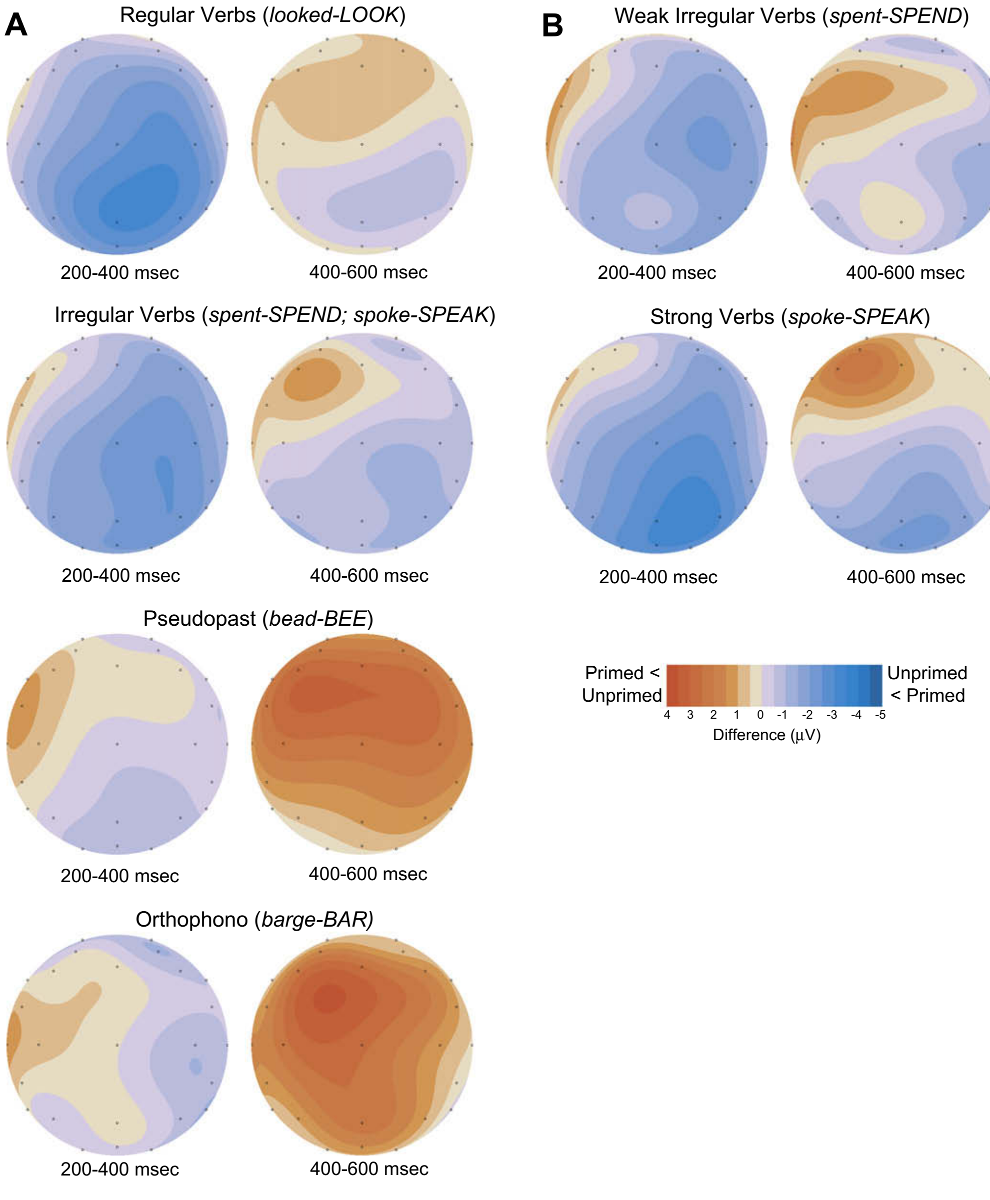

Fig. 3. Topographic maps of the scalp distributions displaying the N400/LPC priming effects (difference between primed and unprimed waveforms) between 200–400 ms and 400–600 ms for (A) each of the four Word Types (regular verbs, irregular verbs, pseudopast, and orthophono), and (B) weak irregular verbs and strong verbs.

distribution of this latter effect suggests that it relates to a distinct ERP component, with a significantly more anterior distribution and showing a trend towards a leftward asymmetry. A suggestion of this effect can be seen in the left anterior quadrant of the regular and irregular verb conditions between 400 and 600 ms as well, where it occurs simultaneously with the latter portion of the N400 effect in the right posterior quadrant. In contrast, this anterior negativity dominates the pseudopast and orthophono conditions. Although this effect overlaps in time with the LPC, the two can be distinguished in both the scalp distribution of the difference waves (left anterior compared to centro-parietal) and polarity (more positive with repetition compared to more negative with onset overlap). As will be explained further, we tentatively name this component the post-lexical anterior negativity, or PLAN.

4.2. Comparison of intra-modal and cross-modal morphological priming

Similar degrees of behavioral facilitation for both regular and irregular primed verbs were found in both the auditory intra-modal study reported by Justus et al. (2008) and the current cross-modal study, replicating previous work using similar intra-modal (Longworth, Keenan, et al., 2005; Marslen-Wilson & Tyler, 1997; Tyler, de Mornay Davies, et al., 2002; Tyler et al., 2004) and cross-modal designs (Kielar et al., 2008, Exp. 2; Basnight-Brown et al., 2007, Exp. 1). In the intra-modal study the priming effects for regular and irregular verbs were 73 and 91 ms, respectively, and in the cross-modal version, 45 and 34 ms, respectively. The smaller priming effects found with visual presentation of the target word is consistent with the faster response times overall found with visual presentation (an average of 651 ms, for correct real-word responses) as compared to auditory presentation (an average of 860 ms from word onset, for correct real-word responses).

These behavioral effects were also associated with N400 priming effects that were observed for both regular and irregular verbs in both the intra-modal and cross-modal experiments, with expected differences in the time course and scalp distribution of the effects (Fig. 4). Specifically, the auditory N400 was larger in size, and lasted longer than did the visual N400. Further, the auditory N400 priming effect did not show a significant hemispheric asymmetry, whereas the visual N400 priming effect was significantly greater over the right hemisphere, in agreement with previous studies (Van Petten & Luka, 2006).

Although both regular and irregular N400 priming effects were significant, the intra-modal study demonstrated that the irregular effect was significantly larger during a later 500–700 ms window, and further that this difference was driven by the strong verbs. The current cross-modal study provides some indications of a replication of this effect, but the data are not as clear on this point. Behaviorally, the strong verbs produced numerically larger priming effects than did the weak irregular verbs, but this interaction was not significant ($p = 0.19$), unlike in the intra-modal study ($p = 0.02$). However, the greater ERP priming for strong verbs compared to weak irregulars was significant for the later analysis window in both studies (both $p = 0.02$). This was sufficient to drive an overall difference between regular and irregular verbs in the later portion of the N400 in the intra-modal study ($p < 0.001$) but not for the LPC in the cross-modal study ($p = 0.33$). Given that the longer lasting ERP priming effect for strong verbs was diminished by using cross-modal rather than intra-modal primes, this might suggest that phonological differences can account for some of the graded effects of regularity observed with intra-modal presentation (Justus et al., 2008). However, phonological factors cannot completely account for these intra-modal effects, given that differences between strong verbs and weak irregular verbs still occurred with cross-modal presentation.

One might argue that the longer lasting priming effect for strong verbs relative to weak irregular and regular verbs was preserved with cross-modal presentation, but that such differences are less easily observed with visual RTs and visual N400 effects. However, subtle differences might be more easily observed with the visual N400, which is shorter and less variable compared to the auditory N400, and with visual lexical decisions, for which response times tend to be generally shorter and less variable than is the case for auditory lexical decisions. Further comparison of the intra-modal data with that of a reverse direction, visual-to-auditory cross-modal priming design would address this issue with more certainty, given that all target words would be auditory while still manipulating the modality of the prime.

4.3. Comparison of intra-modal and cross-modal phonological priming

In contrast to the similarities in priming found for regular and irregular verbs between the intra-modal and cross-modal experiments, the form-based priming represented by the pseudopast and orthophono conditions demonstrated more differences than similarities when comparing the two studies. With intra-modal presentation, both conditions led to significant behavioral facilitation (47 and 63 ms, respectively) as well as an N400 priming effect during the earlier part of the component.

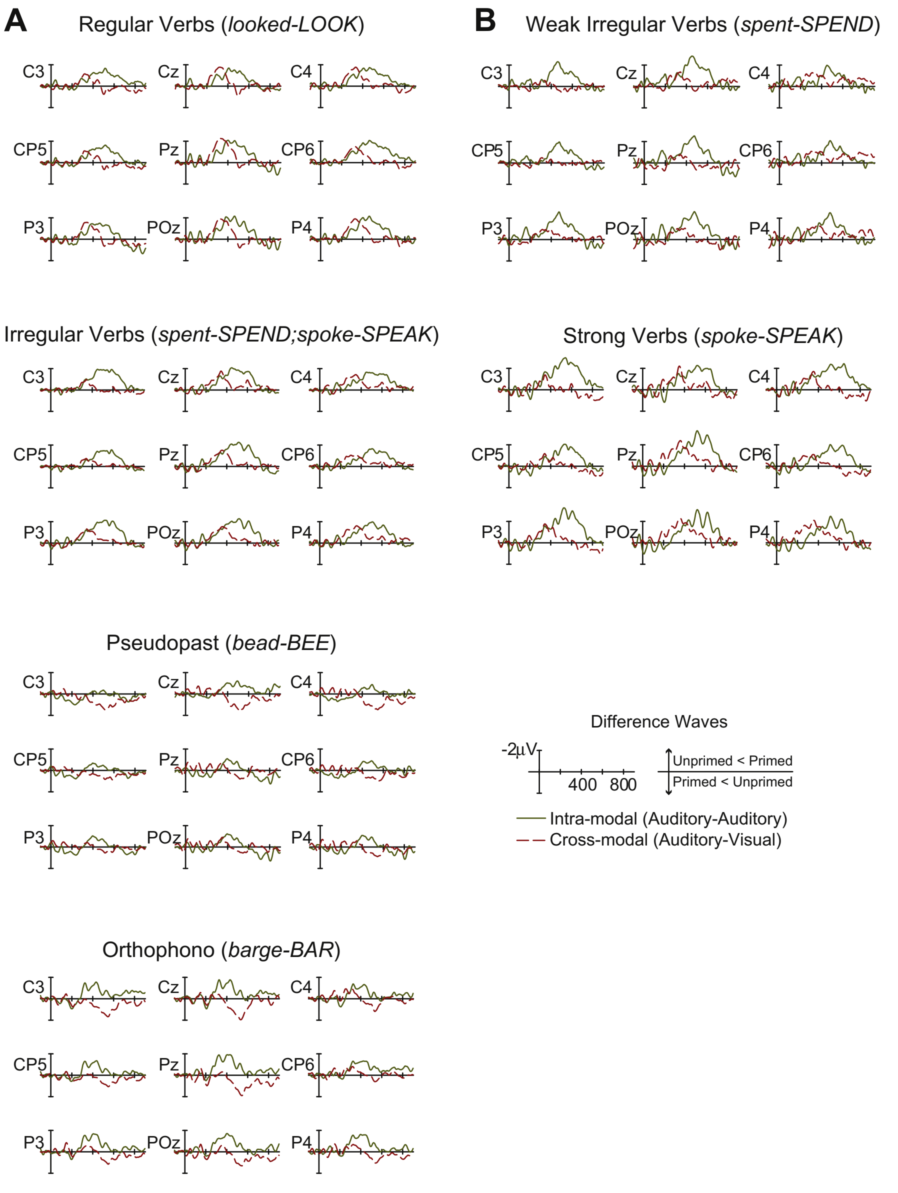

Fig. 4. Difference waves (unprimed minus primed) within the nine-electrode region of interest, combining the results of an auditory intra-modal study (Justus et al., 2008; solid lines) with the present auditory-to-visual cross-modal study (dashed lines). Results are shown for (A) each of the four Word Types (regular verbs, irregular verbs, pseudopast, and orthophono), and (B) weak irregular verbs and strong verbs.

Instead, with cross-modal presentation, behavioral facilitation was significant only for the pseudopast condition (27 ms) and not significant for the orthophono condition (11 ms). Further, no significant N400 priming effects were observed in these conditions with cross-modal presentation. Instead a post-lexical anterior negativity (PLAN), resulting in a reduction of the LPC, was observed for primed conditions sharing word–onset overlap.

Three possible explanations for intra-modal phonological priming effects were discussed in the introduction: prelexical and strategic components, which are likely to be facilitatory, and lexical components, which are likely to be inhibitory (cf. McQueen & Sereno, 2005). With cross-modal presentation, one might expect equivalent degrees of lexical inhibition and similar strategic effects, but a much smaller degree of prelexical facilitation in comparison to intra-modal auditory presentation. The current results are consistent with the notion that prelexical facilitatory priming effects are reduced with cross-modal presentation.

One possible interpretation of the PLAN – the reversed priming effect on the LPC for the pseudopast and orthophono conditions – could be that it represents the lexical inhibition phase of word–onset phonological priming, which was expected to be comparable with both intra-modal and cross-modal presentation (cf. Slowiaczek & Hamburger, 1992). However, the effect displays some similarity to an effect observed by Holcomb, Anderson, and Grainger (2005, Exp. 2) in a study of cross-modal *repetition* priming, in which lexical inhibition would not be expected. These authors found an N400 repetition effect with auditory primes and visual targets, provided that the stimulus-onset asynchrony (SOA) was 800 ms, allowing for the completion of the auditory prime word before the onset of the visual target. The 800-ms SOA also resulted in a reverse-direction repetition effect beginning at around 500 ms, albeit with a broad scalp distribution. This reversal was not observed with visual primes and auditory targets (Exp. 1), nor had it been observed in prior studies of intra-modal and cross-modal studies of semantic priming by the same laboratory (Anderson & Holcomb, 1995; Holcomb & Anderson, 1993). Holcomb et al. (2005) hypothesized that this unexpected effect could reflect “the demands of visual word recognition temporarily blocking semantic processing of the overlapping auditory prime or the delayed buildup of semantic information from the slowly unfolding auditory primes” (p. 506). However, the similar effect in our study, in which the primed and unprimed items did not differ in the degree of semantic relation (e.g., *bead–BEE* compared to *bulb–PIE*), would argue against a semantic interpretation.

Another possible interpretation of the PLAN is that it reflects the confirmation of strategic expectancies related to the formal overlap between primes and targets. Thus, the component would be expected in repetition priming and ortho-phonological priming, and would partially overlap with the N400 in morphological priming, given that morphologically related words overlap both ortho-phonologically and semantically. It is worth pointing out that any strategies used by participants in our studies as well as those of Holcomb and colleagues may be quite similar, given that both studies use a 1:1:1 ratio of related words, unrelated words, and non-words, as well as a pool of non-words that do not contain word–onset overlap with their primes. Thus, conditions were such that participants could have become biased to respond “word” to targets that demonstrated word-initial overlap with their primes. However, we may be able to rule out this concern for the current cross-modal experiment, given the relatively weak behavioral priming effects that were observed with formal overlap. Additional study in which only half of the nonword targets are phonologically related to the prime would address this issue with more certainty.

A related interpretation is that the PLAN reflects a late re-evaluation process that occurs after initial semantic analysis. The failure to observe a difference between primed and unprimed targets in the N400 window suggests that participants correctly recognized that the formally related pseudopast and orthophono targets were semantically unrelated. A post-lexical process may then have confirmed the phonological match between the spoken prime and written target. A very similar effect was observed by Van Petten, Macizo, and O’Rourke (2007) in response to cross-modal, auditory-to-visual priming of embedded words, such that the target represented the final syllable of the prime (e.g., *bovine–VINE*). The scalp distribution (left fronto-temporal) and time course (400–700 ms) of their effect closely resembled what we observed in the present experiment.

Why the PLAN would occur only with cross-modal presentation is unclear. An effect based in lexical inhibition would be expected to occur both intra-modally and cross-modally. Further, an effect based in explicit strategies would likely be as large if not larger in the intra-modal design. One possibility is that the stronger modulation of the N400 in the intra-modal design by prelexical factors obscures the effect.

4.4. Revisiting dual- and single-system models of inflectional morphology

Recent studies of past-tense morphology have begun to explore whether regular–irregular distinctions are better described as categorical or graded (Joanisse & Seidenberg, 2005; Justus et al., 2008, submitted for publication; Kielar et al., 2008; cf. Basnight-Brown et al., 2007). A common theme to these studies is that, when regular–irregular differences are observed, the differences are not categorical, but instead are graded and continuous; weak irregular verbs tend to pattern with regular verbs, whereas strong verbs tend to drive any overall regular–irregular difference.

Specifically, consider the ERP data from the current experimental design. We have first demonstrated that significant priming occurs when the present-tense form of a verb is preceded by the corresponding past tense, regardless of whether the verb is regular or irregular. Importantly, we do not argue that the lack of a dissociation uniquely supports the single-system view, just as we do not argue that dissociations uniquely support the dual-system view. Rather, we must look to the more subtle dissociations that can be observed between the processing of regular and irregular verbs, and ask whether these are categorical, as predicted by dual-system models, or graded, as predicted by single-system models. With this in mind, we find that those portions of the ERP priming effect that diverge when we consider a categorical division between regular and irregular verbs (Fig. 5, left column) may be better represented as a continuous division among regular, weak irregular, and strong verbs (right column). This was observed both using an intra-modal, auditory design (upper row) and a cross-modal, auditory-to-visual design (lower row).

This observation is not easily reconciled with current dual-system theories that posit a bipartite categorical distinction between regular past tenses, which are generated (or understood) by an "add |-d|" (or "strip |-d|") algorithm, and irregular past tenses, which are memorized exceptions to this rule (e.g., Pinker, 1999; Pinker & Ullman, 2002). This approach does not predict that the neurolinguistic profile for weak irregular verbs should ever take an intermediate position between that of regular verbs and strong verbs. Other dual-system approaches that emphasize morpho-phonological parsing (Marslen-Wilson & Tyler, 2007) may be more prepared to accommodate a patterning of regular and weak irregular verbs, which share the weak, dental-stop suffixation pattern, as opposed to the strong verbs, which cannot be parsed in this manner.

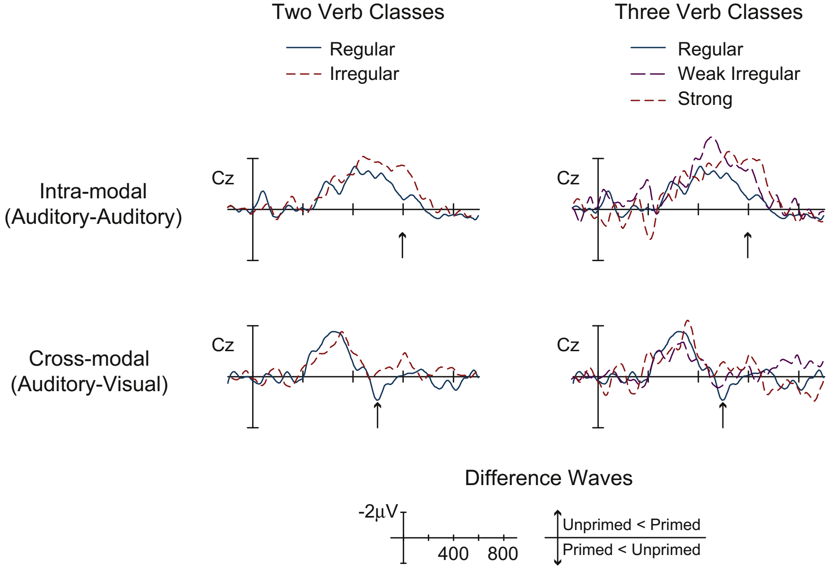

Fig. 5. Difference waves (unprimed minus primed) at electrode Cz, illustrating the verb conditions of both the auditory intra-modal study (Justus et al., 2008; upper row) and the present auditory-to-visual cross-modal study (lower row). The left column displays the verb priming effects as a function of the categorical division of regular and irregular verbs, with arrows indicating the moment of largest numeric difference between the two at approximately 600 ms (intra-modal) and 500 ms (cross-modal). The right column represents the same data as a function of a continuous division of regular, weak irregular, and strong verbs, with arrows indicating the graded and continuous data pattern suggested by the use of three verb classes rather than two.

In contrast, graded and continuous differences between regular and irregular forms are specifically predicted by the connectionist approach. In this view, inflectional morphology is considered to be the convergence of form and meaning (Joanisse & Seidenberg, 1999), a mapping which is full of quasi-regularities, echoing analogous approaches to derivational morphology (Seidenberg & Gonnerman, 2000; Gonnerman et al., 2007) and sound–spelling correspondences in the deep orthography of English (Plaut et al., 1996). This approach would view the division among regular, weak irregular, and strong verbs not as a tripartite categorical division, but rather as suggestive of a underlying continuum of regularity for the past-tense, in which there are no discrete boundaries dividing regularity and irregularity.

5. Conclusions

We have demonstrated that priming between past-tense primes and corresponding present tense targets persists in experimental designs employing cross-modal, auditory-to-visual presentation. Such priming is evidenced by both behavioral facilitation in the lexical decision task, as well as a corresponding reduction in the N400 ERP component to the target word. Further, although such priming is significant and comparable when comparing regular and irregular past tenses, the subset of irregular verbs known as strong verbs seem to drive larger effects in this design, in comparison to regular and weak irregular verbs. This result replicates a stronger dissociation among regular, weak irregular, and strong verbs found with intra-modal presentation (Justus et al., 2008), which we argue is consistent with the connectionist notion of a continuum of regularity in the English past tense.

The current study is also relevant to the issue of ortho-phonological priming between modalities, and in comparison with our earlier intra-modal study provides novel evidence regarding the ERP components associated with word–onset formal priming. With cross-modal, auditory-to-visual presentation, prelexical effects on the N400 appear to be minimized, while a post-lexical anterior negativity (PLAN), resulting in a reduction of the LPC, becomes more prominent.

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