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Short Communication

Auditory morphological processing: Evidence from phonological priming

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ABSTRACT

Using an auditory lexical decision task, we find evidence of a facilitatory priming effect for morphologically complex targets (e.g., *snow-ed*) preceded by primes which rhyme with the target's stem (e.g., *dough*). By using rhyme priming, we are able to probe for morphological processing in a way that avoids confounds arising from semantic relatedness that are inherent to morphological priming (*snow*/*snow-ed*). Phonological control conditions (e.g., targets *code* and *grove* for prime *dough*) are used to rule out alternative interpretations of the effect that are based on partial rhyme or phonological embedding of the stem. The findings provide novel evidence for an independent morphological component in lexical processing and demonstrate the utility of rhyme priming in probing morphological representation.

1. Introduction

1.1. Background

A central issue in the study of the mental lexicon is whether hypothetical morphological representations are activated during real-time processing: Is there independent representation and processing of morphological information or can morphological effects be reduced to interactions between phonology and semantics? In addition to a literature examining frequency effects (see Ford, Marslen-Wilson, & Davis, 2003; Lignos, 2013 for reviews), morphological priming is a dominant methodology for investigating morphological processing. A general issue with morphological priming is that morphological relationships are confounded with semantic and phonological factors: i.e., *played* is phonologically and semantically related to *play*, in addition to hypothetical morphological relatedness (Marslen-Wilson, 2007, 184).

In the auditory domain, long-distance priming, where prime and target are separated by a number of intervening items, is used in an attempt to distinguish morphological priming from effects arising due to semantic and phonological similarity. Marslen-Wilson and Tyler (1998) found morphological priming in the absence of semantic priming at a distance of 12 intervening items. Kouider and Dupoux (2009) report facilitation for morphological priming at long distances (mean 72 intervening items), for which no facilitation for phonological and semantic priming is found. These morphological priming effects show a facilitation strength similar to repetition priming, leading Kouider and Dupoux (2009) to conclude that these morphological effects are independent of phonological and semantic priming.

However, there are explanations for the same type of finding that reject independent morphological processing. In the studies cited above, primes and targets are closely related both phonologically and semantically (*played* is used to prime *play*). As such, the apparent morphological effect can be analysed as an interaction effect between semantic and phonological similarity (see Feldman, 2000; Gonnerman, Seidenberg, & Andersen, 2007). These approaches are able to account for results like those reported in Kouider and Dupoux (2009): Even though phonology and semantics may not have independent effects at long distances, their interaction may still obtain at these long distances. Importantly, this interaction approach relies on the co-presence of shared semantics and phonology for any morphological effects to arise.

The research reported here explores morphological relatedness with *rhyme priming* (e.g., Monsell & Hirsh, 1998; Radeau, Segui, & Morais, 1994; Slowiaczek, McQueen, Soltano, & Lynch, 2000; Slowiaczek, Nusbaum, & Pisoni, 1987), which has been used to investigate phonological processing. Employing this technique to study morphology allows us to eliminate semantic confounds and to control for phonological relatedness in ways that are not possible with morphological priming. Rhyme priming refers to facilitation associated with the phonological notion of *rhyme* (shared vowel and coda consonants): e.g., faster responses to *bunch* after rhyming *lunch* than after non-rhyming *price*. As Norris, McQueen, and Cutler (2002) discuss, facilitatory rhyme priming

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effects seem to be the combination of two separate but additive effects: the presence or absence of rhyme and the amount of final phonological overlap. Slowiaczek et al. (2000) report that a shared *rhyme* (i.e., syllable nucleus + coda) produces significant facilitation, whereas non-rhyming phonological similarity produces only a weak priming effect (e.g., *ranch* only weakly facilitates *bunch*, c.f., Radeau, Morais, & Segui (1995), who found no effect in similar conditions).

Our use of rhyme priming is based on the following premise: If participants process *snow* as part of processing *snowed* because of their morphological relationship, then *snowed* should be facilitated by *dough* because *snow* and *dough* rhyme.

1.2. Experiment

Critical trials test the hypothesis that stems can be phonologically primed in morphologically complex words. Throughout the experiment, primes are semantically unrelated to targets. The experimental conditions each consist of four targets and two primes built around a regular English verb (see Table 1 for an example). The targets were chosen to study the main effect and control for phonological confounds. The BARE STEM target allows replication of previous findings concerning rhyme priming (e.g., *dough* → *snow* vs. *void* → *snow*). The PAST TENSE target consists of the crucial past tense forms (e.g., *dough* → *snowed* vs. *void* → *snowed*).

The remaining two target types control for phonological confounds. The first potential confound is word embedding, which arises due to the incremental nature of auditory speech processing. Responses to words may be influenced by the presence of other *phonologically* embedded words. Thus, for the PAST TENSE condition *snowed*, any facilitation could potentially be attributed to the phonological embedding of the stem *snow*, rather than its morphological structure. The EMBEDDED CONTROL condition consists of words which phonologically embed other words, but do not have concomitant morphological structure (e.g., *grove* embeds *grow*, but *grow* and *grove* are not morphologically related). Comparing the EMBEDDED CONTROL condition *grove* to the PAST TENSE condition *snowed* addresses the potential word embedding confound.

The second potential confound is partial rhyme. The RHYME prime and PAST TENSE target share a syllable nucleus, so any facilitation could be attributed to partial phonological overlap. The PAST TENSE RHYME CONTROL condition *code* provides a non-morphologically complex phonological control for the PAST TENSE condition (since *code* is not decomposable into real stem and affix). As the PAST TENSE RHYME CONTROL condition rhymes with the PAST TENSE condition, targets in these conditions always have the same partial phonological overlap with the RHYME condition prime. Therefore, comparison of these conditions excludes any facilitation which is due to a partial rhyme confound.

The PAST TENSE RHYME CONTROL condition also addresses the issue of segmentation effects for words with an "inflectional rhyme pattern" (IRP). An IRP is a word-final coronal consonant (/d, t, s, z/) that shows agreement in voice between the final coronal consonant and the preceding segment. Segmentation effects for stems

Table 1
Examples of the experimental conditions (prime rhyme status is determined with respect to the Bare Stem target).

	Bare stem	Past tense	Past tense rhyme control	Embedded control
Non-Rhyme Prime	void	void	void	void
Rhyme Prime	dough	dough	dough	dough
Target	snow	snowed	code	grove (*grow* embedded)

and pseudo-stems in IRP words have been reported (e.g., Bozic, Tyler, Ives, Randall, & Marslen-Wilson, 2010; Post, Marslen-Wilson, Randall, & Tyler, 2008). However, facilitated processing of pseudo-stems (e.g., *co-* in *code*) due to rhyme priming may not facilitate responses to the IRP word, as pseudo-stem facilitation may interfere with word recognition. As such, if these segmentation effects are at play, we would not necessarily predict facilitation in responses in the PAST TENSE RHYME CONTROL condition.

In summary, theories with independent morphological processing predict that a rhyming prime *dough* will facilitate access to *snowed* via its morphological relationship with *snow*. Current theories without independent morphological processing would not be able to account for such an effect, since they rely on capturing morphological effects via interactions between semantic and phonological factors, and the semantic factors are absent in this experiment. Finally, if phonological overlap alone were responsible for facilitation effects, *dough* and *snowed* should behave like the phonological controls: that is, either identically to the EMBEDDED CONTROL condition *grove*, due to phonological embedding; or to the PAST TENSE CONTROL condition *code*, due to non-rhyming phonological overlap. Thus, to the extent that we find (increased) facilitation to morphologically complex (*snowed*) targets, this can be attributed to morphological processing independent of shared semantics and phonology.

2. Methods

2.1. Participants

34 native English speaking participants were recruited through the university subject pool. Participants were compensated with course credit.

2.2. Stimuli

Each critical item included a group of two primes and four targets built around a single regular verb. Stimuli consisted of 96 critical words (forming 16 critical items), 64 phonotactically licit non-words, and 32 filler words (see the online supplement for a list of items). One critical item was excluded from analysis, because it was determined not to satisfy our control criteria after the experiment had been run. Non-words and fillers did not rhyme with any other item in the experiment. As much as possible, stimuli were matched for SUBTLEX(US) frequency (Brysbaert & New, 2009). All stimuli were recorded by a male speaker of Standard American English.

2.3. Procedure

The experiment was run using Psychopy (Peirce, 2007) and responses were recorded using an Empirisoft Rotary Controller. Stimuli were presented to the participants binaurally through headphones in a continuous lexical decision task, with a random ISI between 400 and 600 ms. The ISI was measured from the end of the sound file or participant response, whichever was later.

Before the experiment, subjects performed 6 practice trials (4 word, 2 non-word). The experiment had 8 blocks with a break between blocks 4 and 5. In each block, participants saw one of the 8 conditions for each of the 16 critical items as well as all of the fillers. Fillers were repeated in each block. All subjects saw all conditions for all critical items. Participants were sequentially assigned to one of eight groups.

In order to maximise the distance between two tokens of the same target, the experiment was divided in half (blocks 1–4 and blocks 5–8). For the critical items, a Latin square design (across

Table 2
Example of the distributions of conditions for a single item in a single group.

Block	Prime	Target
1	Rhyme (*dough*)	Bare stem (*snow*)
2	Non-rhyme (*void*)	Past tense (*snowed*)
3	Rhyme (*dough*)	PT rhyme control (*code*)
4	Non-rhyme (*void*)	Embedded control (*grove*)
5	Non-rhyme (*void*)	Bare stem (*snow*)
6	Rhyme (*dough*)	Past tense (*snowed*)
7	Non-rhyme (*void*)	PT rhyme control (*code*)
8	Rhyme (*dough*)	Embedded control (*grove*)

the 8 groups) was used to distribute the four target conditions across the first four blocks. Each block (1–4) alternated between a rhyme prime and non-rhyme prime for each item. The same order of targets was used in the second half of the experiment, but with the opposite prime (see Table 2). In addition to the effect of rhyme priming, we expect an effect of repetition priming between the first and second instance of the same target, which we controlled for in our analyses.

For each block, all of the filler items were randomly combined to create 24 non-word–non-word pairs, 8 word–word pairs, 8 non-word–word pairs, and 8 word–non-word pairs. Therefore, not all sequences of two words were critical items and the experiment contained a balanced set of words and non-words.

2.4. Analyses

Responses were coded for response type (word/non-word) and reaction time measured in milliseconds from the start of the sound file with differences in duration included as a predictor in the model. Responses shorter than the duration of the sound file (∼4% of the trials), longer than 5000 ms (∼1.5%), or for which either the prime (∼16%) or target (∼10%) response was incorrect were excluded (∼23%). Data were analysed in R using linear mixed effects regression fitted with lme4 version 1.1–7. We followed a procedure based on Bates, Kliegl, Vasishth, and Baayen (2015) to find the most parsimonious random effect structure, starting with a model that included the full set of predictors for both subject and items, as well as an intercept for a subject–item interaction random effect. The final random effect structure can be found in the online supplement.

Our dependent variable was -1000^{*} inverse transformed reaction times (Baayen & Milin, 2010). We began by fitting a model predicting the transformed reaction time with the following critical independent variables: Prime Type (RHYME/NON–RHYME), Target Type (BARE/PAST TENSE/RHYME CONTROL/EMBEDDED CONTROL), Repetition Status (first instance/second instance). Prime Type and Repetition Status were coded with sum contrasts with the following levels assigned the value -1: non–rhyme and first instance. Target Type was coded with a treatment contrast with the past tense target as the control and three different variables to investigate whether other target types differed from the PAST TENSE target. We also fitted two planned follow-up models that used only the PAST TENSE RHYME CONTROL and EMBEDDED CONTROL data. These models were used to see if there was any significant effect of prime type in those conditions.

In order to control for alternative explanations of the results, we included normalised variables corresponding to the prime and target items' Latent Semantic Analysis value based on college freshman's vocabulary (Landauer, McNamara, Dennis, & Kintsch, 2013), target duration, target frequency, target entropy before the vowel, target entropy after the vowel, and their interactions with the Target Type variable. In addition to controlling for repetition of the targets, we also included whether the stem had already been seen to control for long distance stem priming effects. We calculated a quantitative measure of acoustic similarity using Mel-Frequency Cepstral Coefficients and Dynamic Time Warping (Muda, Begam, & Elamvazuthi, 2010, using the implementation in Boersma & Weenink, 2015). Similar results were found when Prime Type was replaced with this more fine grained measure of phonetic similarity. Results discussed below are from the simpler models with Prime Type. P-values were calculated using the Satterthwaithe approximation to degrees of freedom (Kuznetsova, Brockhoff, & Christensen, 2015). We also fitted profile confidence intervals and report as significant only effects with *p*-values less than.05 and confidence intervals not including 0.

3. Results and discussion

After removing trials with unreasonably short or long reaction times, inaccurate trials were also removed as discussed above. There was no correlation between critical condition and accuracy. Since the design was within-subjects, the raw means contain effects from repetition priming and rhyme priming. Therefore, only predicted results from models are reported here. The raw results, data summaries and the relevant R code can all be found in the online supplement.

As expected, repetition priming was significant in all conditions, as seen by a significant simple effect of repetition status ($p < 0.001$) and the lack of significant interaction between repetition status and any of the three target type variables ($p = 0.377$, 0.969, 0.558). In addition, there were no significant interactions between repetition status and prime type for any of the targets ($p = 0.207$, 0.694, 0.159, 0.435), suggesting that target repetition and rhyme priming are orthogonal processes, legitimising the within-subjects design. According to the large model, both the BARE STEM targets and EMBEDDED CONTROL targets were significantly slower than the other two conditions, even when controlling for duration independently of prime type. Identifying the source of this difference in raw RT requires further investigation.

Crucially, participants responded significantly faster to the past tense target *snowed* after the rhyming prime *dough* than after the non-rhyming prime *void* ($p < 0.001$). The size of the priming effect can be seen in Fig. 1. There was no significant interaction between prime status and the BARE STEM target ($p = 0.952$). The rhyming prime *dough* and the BARE STEM target *snow* exhibit full rhyme, so we conclude that faster responses to BARE STEM targets after the rhyming prime is due to rhyme priming (Slowiaczek et al., 1987 *inter alia*). As we found no significant difference in the effect of prime type between the PAST TENSE and BARE STEM conditions, we conclude that the effect of prime type is attributable to rhyme priming in both. The fact that both *snow* and *snowed* showed the same degree of priming is thus consistent with the theory that *snow* is accessed as part of the access of *snowed*.

The priming effect occurred only where a morphological relationship is hypothesised: significant interactions between prime type and PAST TENSE RHYME CONTROL ($p = 0.007$) and the EMBEDDED CONTROL ($p = 0.006$) indicated a significant difference in the effect of the prime in those conditions. In models fit to only data from those conditions, neither the PAST TENSE RHYME CONTROL ($p = 0.735$) nor the EMBEDDED CONTROL ($p = 0.951$) showed any significant rhyme priming effect, suggesting that neither word embedding nor partial rhyme are responsible for the priming effect found with the past tense targets. The same patterns obtained when raw phonetic similarity was used as a proxy for prime type, which suggests that the rhyming effect was not driven by clustering of phonetic similarity between prime and target in the BARE STEM/PAST TENSE conditions.

Our results provide evidence for Independent Morphological Processing (IMP) in ways that avoid confounds inherent to the morphological priming technique, which to date has been a pre-

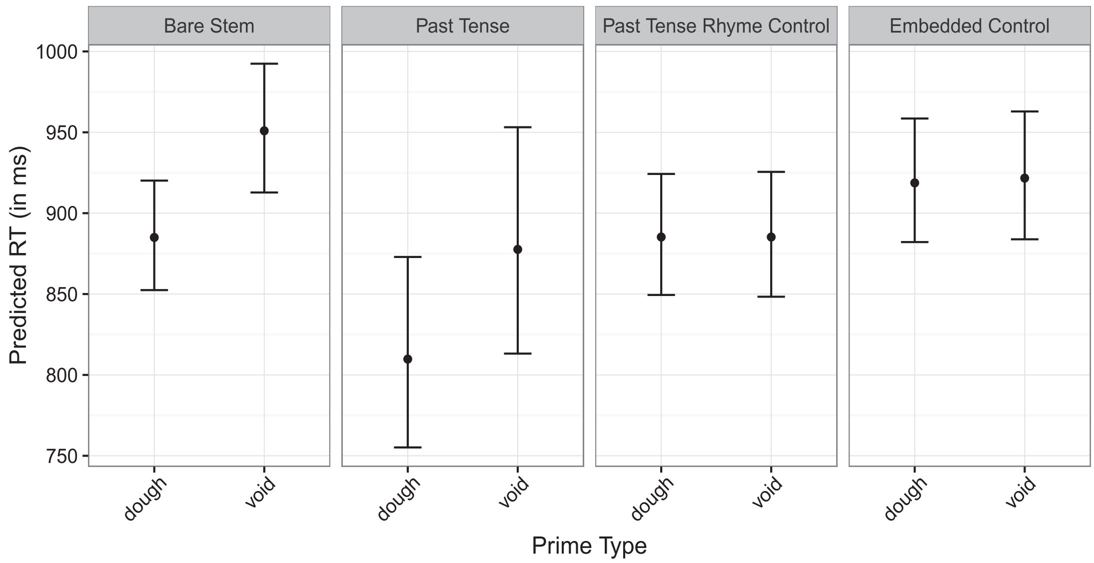

Fig. 1. Predicted RT in each condition based on the fixed effects and standard errors from the model for a word of average frequency, duration, LSA, acoustic similarity, and entropy profile (factoring out repetition priming).

dominant method of probing morphological representation. Priming between pairs like *played* and *play* involves a (hypothesised) morphological relationship, but also involves considerable semantic and phonological overlap. This leaves open the possibility that effects attributed to morphological processing can be attributed solely to sound/meaning overlap, without IMP. Essentially all work arguing for IMP on the basis of morphological priming is subject to this objection. Crucially, because of the methodological innovation of studying morphology using rhyme priming, our evidence for IMP involves primes bearing no semantic relationship to targets. Thus, there is no possibility for an alternative explanation of our results using the interaction of shared semantics and phonology. Moreover, our phonological control conditions, which employ phonological overlap and the embedding of actual words within the targets, demonstrate clearly that the rhyme priming effect for morphologically complex words is not driven by purely phonological factors.

Regarding our conclusions, we have been careful to restrict our discussion to the support our findings provide for IMP. This is a significant result because of the importance of models in which morphological relationships are epiphenomenal. It is important to note that our results do not further distinguish among different ways of modelling IMP that have been discussed in the literature. For instance, while many theories posit that complex words are *decomposed* into constituent morphemes that are each represented in memory (Marslen-Wilson, 2007; Taft, 2004), other approaches invoke IMP, but without decomposition in this sense. Baayen, Dijkstra, and Schreuder (1997), for example, argue for a non-decompositional account of morphological processing, where bare stems are related to complex words via rules or associations rather than having prefixes and suffixes stored as independent pieces. Other techniques, including but not limited to affix priming (see Amenta & Crepaldi, 2012), must be employed in order to examine the finer details of IMP.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2017.03.011.

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