Towards a theory of multimorphemic word production: 
The Heterogeneity of Processing Hypothesis

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Abstract

Theories of spoken production have not yet addressed the post-lexical processing of multimorphemic words, that is, how a multimorphemic word’s phonological form is prepared for production. This paper reviews what is known about how multimorphemic words are represented in production at lexical and post-lexical stages as well as the influence that lexical properties have on post-lexical processes. A proposal linking these facts together is presented which predicts that post-lexical processes 1) should be weaker when acting across morpheme boundaries and 2) should be influenced by the lexical properties of each morpheme. Post-lexical processing is thus predicted to vary, or be ‘heterogeneous’, across a multimorphemic word. Phoneme competition (as indexed by inhibitory effects of phoneme similarity) is compared within and across morphemes in three analyses of oral reading latencies. Competition is found to be weaker across morpheme boundaries, providing support for heterogeneity.
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Introduction

Although there has been extensive psycholinguistic research investigating the lexical aspects of multimorphemic word processing—examining, for example, whether morphologically complex words are represented in a decomposed (morpheme-based) or holistic (word-based) fashion (e.g., Butterworth, 1983; Caramazza, 1997; Fiorentino & Poeppel, 2007; Marslen-Wilson & Zhou, 1999; Stockhall & Marantz, 2006; Taft, 2004; Bybee, 1995; Elman, 2004; Kuperman, Schreuder, Bertram, & Baayen, 2009; Rubin, Becker, & Freeman, 1979; Seidenberg & Gonnerman, 2000), which factors contribute to productivity (e.g., Anshen & Aronoff, 1981; Baayen, 1994; Bauer, 2004; Cutler, 1980a, 1981; Hare & Elman, 1995; Hay & Baayen, 2003; Hay & Plag, 2004; Krott, Baayen, & Schreuder, 1999; Marchman, Wulfeck, & Weismer, 1999; Plag, 1999), and whether paradigmatic relations influence processing (e.g., Baayen, Levet, Schreuder, & Ernestus, 2008; Ernestus & Baayen, 2007; Juhasz & Berkowitz 2011; Kuperman, Pluymaekers, Ernestus, & Baayen, 2007; Milin, Kuperman, Kostic, & Baayen, 2009; Moscoso del Prado Martin, Kostic, & Baayen, 2004)—relatively little is known about the post-lexical processing of multimorphemic words in production. Collectively, post-lexical processes are responsible for computing a word’s phonological form for production and comprise phonological encoding, the process by which phonemes are retrieved and ordered, grammatical phonological processing, where the phonological form of a word is adjusted to conform to language-specific and universal well-formedness constraints, and articulatory planning, where gestural scores and motor plans governing the movement of the articulators are generated.

Current theories of spoken production, although they provide accounts of the
lexical processing of multimorphemic words, are silent as to how these words are
processed at post-lexical levels (Dell, 1986; Levelt, Roelofs, & Meyer, 1999). While the
default assumption could be that mono- and multimorphemic words undergo identical
post-lexical processing (e.g., there is no difference in the way that the phonological forms
of band and banned are computed), a number of studies have found differences in the
phonetic realization of mono- and multimorphemic words, indicating that differences
exist in the way they are processed at post-lexical levels (Cho, 2001; Frazier, 2006;
Losiewicz, 1995; Schwarzlose & Bradlow, 2001; Sugahara & Turk, 2009; Walsh &
Parker, 1983). Other studies have supported this assertion, finding that word-internal
morphemes are important planning units in phonological encoding (Roelofs, 1996a;
Roelofs & Baayen, 2002). To date, no general theory describing the way that post-lexical
processes operate over multimorphemic words has been proposed. Once a
multimorphemic word has been retrieved from the lexicon or assembled productively,
how is its phonological form computed? What effect, if any, does its lexical structure
have on post-lexical processing?

This paper represents a first attempt to bring what is known about lexical and
post-lexical processing in spoken production to bear on the issue of the post-lexical
processing of multimorphemic words. The rest of the Introduction is organized as
follows. First, evidence concerning the structure of multimorphemic words at lexical and
post-lexical stages of processing is reviewed. Then, psycholinguistic data concerning the
influence that lexical representations have on post-lexical processing is reviewed. These
facts are then brought together into a theory of multimorphemic word processing termed
the Heterogeneity of Processing Hypothesis (HPH). This hypothesis predicts that post-
lexical processing will vary across a multimorphemic word in two ways: 1) post-lexical processes should apply more weakly across morpheme boundaries than to phonemes within the same morpheme and 2) post-lexical processes should vary according to the lexical properties of each morpheme. Evidence from three analyses of oral reading latency data are then reported that support the first prediction of the HPH.

The lexical representation of morphologically complex words in production

Theories of spoken production hold that lexical representations are important planning units in the production of words (in the rest of this article, the terms ‘morpheme’ and ‘lexical unit’ will be used interchangeably). Fundamentally, the morpheme is thought to mediate between semantic and phonological processing—rather than directly activating phonology, semantic representations activate lexical representations, which in turn provide access to the word’s phonological form. This ‘two-step’ organization thus divides word production into two main components: the selection of lexical items on the basis of their fit to semantic and/or syntactic specifications and the retrieval and planning of the word’s phonological form. This distinction has been successful in accounting for a variety of experimental findings (e.g., Dell & O’Seagdha, 1992; Jescheniak & Levelt, 1994; Kempen & Huijbers, 1983; Levelt & Maassen, 1981; Levelt et al., 1991; Schriefers, Meyer, & Levelt, 1990; Levelt, Roelofs & Meyer, 1999) as well as speech errors in normal (e.g., Dell, 1986; Fromkin, 1971; Garrett, 1975, Butterworth, 1989) and impaired individuals (e.g., Dell, Schwartz, Martin, Saffran, & Gagnon, 1997; Saffran, Schwartz, & Marin, 1980, Bock, 1987).

A major debate in both the comprehension and production literatures is whether
morphologically complex words are represented at lexical levels as whole words or in terms of their component morphemes. In production, the question centers on what units provide access to a word’s phonological form: ‘full-listing’ theories argue in favor of a single representation (e.g., a single lexical representation provides access to all of the phonemes in the word *sunshine*; Butterworth, 1983; Caramazza, 1997) while ‘compositional’ theories argue in favor of multiple representations (e.g., one representation provides access to the phonemes /s/, /ʌ/, /n/ while another provides access to /ʃ/, /aɪ/, /n/; Levelt et al., 1999).

Currently, a substantial body of evidence supports the notion that production utilizes compositional, morpheme-based representations (see Bölte, Zwitserlood, & Dohmes, 2004 for a review). Some of the evidence for this position comes from morpheme-level speech errors in neurologically intact (Cutler, 1980; Fromkin, 1973; Garrett, 1975, 1980; Melinger, 2003; Pillon, 1998; Stemberger, 1982) and impaired individuals (Badecker, 2001; Badecker & Caramazza, 1991; Cholin, Rapp, & Miozzo, 2010; Cohen-Goldberg, Cholin, Miozzo, & Rapp, submitted; Delazer & Semenza, 1998; Hittamair-Delazer, Andree, Semenza, De Bleser, & Benke, 1994; Miceli, Capasso & Caramazza, 2004; Mondini, Luzzatti, Zonca, Pistarini & Semenza, 2004; Stemberger, 1985). Some studies of aphasic individuals have found effects of morpheme frequency in compound production where high frequency constituents are more accurately produced than low frequency constituents, providing detailed evidence for the existence of component morphemes (Ahrens, 1977; Blanken, 2000; Rochford & Williams, 1965).

Other data come from chronometric studies that find morpheme-specific effects in word production (Bien, Levelt, & Baayen, 2005), implicit priming (Roelofs, 1996a,
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1996b; Roelofs & Baayen, 2002), and the picture-word interference task (Bölte, Dohmes, & Zwitserlood, 2012; Lüttmann, Zwitserlood, Böhl & Bölte, 2011; Zwitserlood, Bölte, & Dohmes, 2000, 2002). Interestingly, some of the studies that have found evidence for component morphemes have found these effects in semantically opaque (e.g., Badecker, 2001; Lüttmann et al., 2011; Roelofs & Baayen, 2002) and morphologically irregular words (Cholin, Rapp, & Miozzo, 2010), suggesting that morpheme-based representations are not restricted to only the most productive words. Studies have also suggested that written production makes use of morpheme-based representations, providing converging evidence for the role of the morpheme in production (e.g., Badecker, Hillis & Caramazza, 1990; Badecker, Rapp & Caramazza, 1996).

The evidence is not completely decisive in favor of morpheme-based representations, however. Some production studies have found evidence for both morpheme-based and whole-word representations (e.g., Bien et al., 2005; Tabak, Schrueder, & Baayen, 2010), suggesting that whole-word representations may influence production in addition to morpheme-based representations (supporting ‘dual-route’ theories, e.g., Baayen, Dijkstra & Schreuder, 1997; Jackendoff, 1975). At the same time, a handful of studies have failed to find evidence for morpheme-based representations while finding evidence for whole-word representations (Chen & Chen, 2006, 2007; Ernestus, Lahey, Verhees & Baayen, 2006; Janssen, Bi & Caramazza, 2008).

Despite some variation in the findings, there is strong evidence that morphologically complex words are represented in a morpheme-based format (and perhaps, in addition, as whole words) in production.
The post-lexical representation of morphologically complex words in production

Despite the differences in their lexical representation, it is possible in principle that mono- and multimorphemic words are represented identically at post-lexical stages of processing (e.g., band and ban+ed = /bænd/). This state of affairs would be predicted, for example, if post-lexical representations could only contain phonological information (e.g., Hockett, 1942; Joos, 1964). There is reason to believe, however, that post-lexical representations do in fact differ depending on a word’s morphological structure. In this section, evidence is reviewed that post-lexical representations of multimorphemic words contain 1) explicit information about morphological boundaries and 2) fewer/weaker structural relations between the content of different morphemes.

As Roelofs (1996b) notes, grammatical phonological processes provide evidence that morphological boundaries must be explicitly marked in post-lexical representations. Phonologists have long noted that languages contain phonological rules that make reference to word-internal morpheme boundaries. Some rules are triggered by the presence of such boundaries (e.g., Finnish assibilation converts /t/i/→[s] when followed by /i/, but only when spanning a morpheme boundary: /tilat+i/→[tilasi], not *[silasi]; Kiparsky, 1973) while others are blocked (e.g., the roots of a compound are independent domains of syllabification in English, preventing syllabification from occurring across the compound boundary: cf. ni.trate vs. night.rate). The existence of active, synchronic rules of this sort indicates that morpheme boundaries are represented in some way in post-lexical representations. Phonological theories have proposed that boundaries are explicitly marked, either by special boundary symbols (e.g., + and #, Chomsky & Halle, 1968), indirectly through hierarchical prosodic structure (e.g., the phonological word;
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Nespor & Vogel, 1986; Selkirk, 1984), or through morpheme affiliation labels (e.g. morpheme ‘color’, van Oostendorp, 2005). Since morphophonological rules operate as expected over novel, productively formed words (e.g., the novel compound sprite race would be pronounced [sprat.reɪs], not *[sprat.tres]), the insertion of morphological information must occur during the process of concatenating the individual phonological representations.

In addition to containing explicit boundary information, a number of studies have suggested that the post-lexical representations of multimorphemic words are weaker in some fashion (or that phonemes are more ‘loosely’ joined together) at morpheme boundaries. Using articulatory measurements of Korean homophones that differ only in morphological structure (e.g., /nap+i/ vs. /nap/i/), Cho (2001) found that intergestural timing was more variable when the gestures corresponded to heteromorphemic sequences (e.g., /p+i/) than tautomorphemic sequences (e.g., /pi/). Hay (2003) reported broadly similar results for multimorphemic words that vary in their lexical structure. In a phonetic study of English suffixed words, Hay compared the rate of interconsonantal /t/-deletion (a variable rule that deletes /t/s in the environment CtC, where ‘C’ indicates a consonant) in words that are likely to have a morpheme-based representation (e.g., daftly, which is less frequent than its root daft) and in words that are likely to be processed as wholes (e.g., swiftly, which is more frequent than swift). Hay found that /t/-deletion was weaker in the words that are likely to have morpheme-based representations and more robust in the words likely to have whole-word representations.

1 See Kiparsky (1982) and Monahan (1982) for a different approach to the relationship between morphology and phonology. See also Scheer (2011) for an excellent overview of the various ways that phonological theory has encoded non-phonological information in phonological representations.
Both of these studies suggest that post-lexical content from different morphemes is less well-integrated than content from the same morpheme. Articulatory gestures appear to not be as well-coordinated in time across a morpheme boundary and phoneme sequences created from multiple morphemes appear less likely to trigger phonological/phonetic processes. Consistent with this notion, Cho’s results have been modeled within the framework of Articulatory Phonology by assuming that there are fewer timing relationships between heteromorphemic than tautomorphemic gestures (Nam & Saltzman, 2003).

One final piece of evidence suggesting that post-lexical representations contain structural weaknesses at morpheme boundaries comes from the case of a brain-damaged individual, WRG, who made discrete phonological repairs between word-internal morphemes but not within morphemes themselves (Cohen-Goldberg et al., submitted). In their investigation, Cohen-Goldberg and colleagues first determined that WRG’s stroke impaired his lexical phonological processing while leaving his post-lexical processing relatively intact. This dissociation was indicated by a stark difference between his performance in picture naming (which requires lexical processing) and repetition (which only requires post-lexical processing). When given drawings of objects with monomorphemic names, WRG was only able to name 12% of the items but when he was administered monomorphemic words for repetition, WRG was able to correctly repeat 89% of the items (97% accuracy by phoneme). WRG’s inability to name objects indicates that he suffered from a severe lexical deficit while his ability to repeat words reveals that his post-lexical phonological processing was relatively intact (he was still able to plan and articulate the sounds of words).
Cohen-Goldberg and colleagues report that when producing multimorphemic words in elicitation or reading, WRG frequently made insertion errors that improved (or ‘repaired’) the phonological structure of the word. For example, when producing words suffixed with the past tense, WRG frequently inserted segments in between the root and the suffix (e.g., walked → [wakɪt]) or after the suffix (e.g., slipped → [slɪptɪd]). Cohen-Goldberg et al. demonstrated that WRG was significantly more likely to make these insertion errors when the words contained phonologically marked obstruent-obstruent coda clusters (insertion rate: 27%) than when they contained relatively less marked sonorant-obstruent clusters (5%). The errors improved the phonological structure of the coda by separating the coda consonants into different syllabic positions ([waˌkɪt]) or by re-syllabifying them into different syllables ([slɪpˌɪtd]). Intriguingly, WRG was able to repeat the same words with near perfect accuracy, ruling out an articulatory locus for his impairment.²

The key comparison came when WRG’s performance on coda clusters in suffixed words (e.g., banned, walked) was compared to his performance on similarly structured tautomorphemic environments (e.g., grand, fact). In contrast to his performance on suffixed words, WRG’s insertion error rate on tautomorphemic coda clusters did not differ between obstruent-obstruent (8%) and sonorant-obstruent codas (5%). The fact that WRG’s errors were driven by phonological markedness coupled with

² A similar pattern was observed in the case of stress, where WRG inserted segmental material in words containing stress clash (the dispreferred arrangement of stress on adjacent syllables, e.g., brīsknēss → [briskidnes̩], unīquenēss → [junikidnes̩]; insertion rate: 32%) but not in words without stress clash (clēvernēss; 0%). WRG never made these errors in repetition. As with the past tense-suffixed words, these insertions improved the phonological structure of the targets, in this case by separating the stressed syllables with an unstressed epenthetic syllable.
the pre-articulatory locus for his impairment led Cohen-Goldberg and colleagues to conclude that WRG’s phonological grammar was responsible for the insertions, which were made in part to improve the words’ well-formedness. For the present purpose, the contrasting pattern of repairs in tauto- and heteromorphemic environments supports the notion that heteromorphemic phonemes are more loosely joined than tautomorphemic phonemes. Cohen-Goldberg and colleagues argued that WRG’s lexical damage impaired his ability to combine the phonological content of different morphemes, severely weakening the strength with which phonemes from different morphemes are bound together. This weakening allowed the phonological grammar to express itself through phonological repairs at the morpheme boundary. In monomorphemic words—where post-lexical representations do not need to be assembled from different morphemes—phonemes were bound to each other sufficiently strongly to prevent the grammar from making similar repairs in tautomorphemic environments.

A variety of evidence thus suggests that the post-lexical representations of multimorphemic words differ from those of monomorphemic words in that they contain explicit representation of the original morphological boundaries and structural weaknesses at the morphological boundary. It seems likely that these weak points are somehow related to the need to bind together on the fly phonemes from different morphemes (Cho, 2001; Cohen-Goldberg et al., submitted).

*Lexical influences on post-lexical processing*

Having reviewed the representations of multimorphemic words at lexical and post-lexical levels, one final element is needed in order to understand how
multimorphemic words are processed at post-lexical levels, which is to understand how lexical representations influence post-lexical processing in the general case. As will now be reviewed, spoken production research on the processing of monomorphemic words has shown that the two-step organization of speech, by allowing lexical representations to mediate access to phonological representations, has profound consequences for post-lexical processing.

The fact that morphemes provide access to phonological representations affects post-lexical processing in a variety of ways. The simplest consequence is that morphemes influence the onset of post-lexical processing. Since morphemes provide access to a word’s phonological form, the sooner a morpheme is accessed, the sooner its phonemes will receive activation and the sooner post-lexical processing may begin. All things being equal, for example, post-lexical processing will begin earlier for a high frequency word than for a low frequency word. Morphemes similarly mediate the scope of post-lexical processing, since all of a morpheme’s phonemes are simultaneously activated during retrieval (see Cohen-Goldberg, 2012 and the references therein).

Beyond affecting the timing of processing, lexical representations have significant effects on the computations performed by post-lexical processes. High frequency words and words with many phonological neighbors are processed more accurately at post-lexical stages, resulting in fewer sound-based errors in both neurologically intact (Dell, 1990; Harley & Brown, 1998; Stemberger & MacWhinney, 1986; Vitevitch, 2002) and brain-damaged individuals (Goldrick, Folk, & Rapp, 2010; Knobel, Finkbeiner, & Caramazza, 2008). These effects have typically been modeled via cascading activation from lexical to phoneme levels, with more activation leading to faster and more accurate
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processing (Knobel et al., 2008). Lexical properties such as frequency, neighborhood
density, and predictability have also been shown to influence the outcome of post-lexical
computations, affecting a wide variety of phonetic properties such as vowel space (Aylett & Turk, 2006; Gahl, Yao, & Johnson, 2012; Munson & Solomon, 2004; Wright, 2004),
tone space (Zhao & Jurafsky, 2007), VOT (Baese-Berk & Goldrick, 2009), coarticulation
(Scarborough, 2004) and duration (Aylett & Turk, 2006; Bell, Jurafsky, Fosler-Lussier,
Girand, Gregory, & Gildea, 2003; Bell, Brenier, Gregory, Girand & Jurafsky, 2008; Gahl,
2008; Gahl et al., 2012). Lastly, morphemes have been theorized to provide access to
stored motor plans, allowing word-specific articulatory parameters to surface in speech
(Bybee, 2001; Goldrick, Baker, Murphy, & Baese-Berk, 2011; Pierrehumbert, 2003;

To summarize: the lexically mediated organization of speech production has
significant implications for post-lexical processing, influencing its onset, accuracy, and
outcome, and the extent to which articulatory plans are retrieved vs. computed for the
word.

The post-lexical processing of morphologically complex words: the Heterogeneity of
Processing Hypothesis

The Heterogeneity of Processing Hypothesis (HPH), which will now be
described, brings together the empirical generalizations referenced above into a theory of
how post-lexical processing occurs for multimorphemic words. The HPH takes as its
starting place the fact that morphologically complex words are represented by multiple
lexical representations (morphemes).

The first consequence of this organization, termed *Morpheme Assembly*, is that post-lexical representations must be assembled in some fashion during production. Since each morpheme activates only its constituent phonemes, phonemes from different morphemes must somehow be ‘bound’ together in order to create an integrated phonological representation that can drive post-lexical processes. This assembly process, though currently underspecified in theories of spoken production, likely involves—at the very least—updating segmental position information to reflect the newly constructed multimorphemic environment (e.g., the /k/ in *cloth* is no longer in word-initial position when it appears as part of the compound *tablecloth*). Stored articulatory plans, should they exist for the morphemes in question, must similarly be joined together.

Based on the evidence described earlier, the process of assembling post-lexical representations appears to leave boundary symbols and structural weaknesses at morpheme boundaries in the post-lexical representation. This leads to the first prediction of the HPH, which is that *post-lexical processes will apply more strongly to tautomorphemic phonemes than heteromorphemic phonemes*. These ‘fault-lines’ at in the post-lexical representations are proposed to cause each morpheme to act (to a certain extent) as a processing domain for post-lexical processes, resulting in heteromorphemic phonemes being less phonologically integrated with each other (e.g., less coarticulated) than tautomorphemic phonemes.

The second consequence of the morpheme-based organization of morphologically complex words, termed here *Segregated Lexical Inheritance*, is that phonemes in a multimorphemic word will inherit the lexical properties of the morpheme they belong to.
Given the two-step organization of speech production, each morpheme provides access to only its constituent phonemes and as a result, each phoneme in turn is influenced by the properties of its parent morpheme. This means that across the word, phonemes will be influenced by different lexical properties: phonemes will receive different levels of activation as a result of, e.g., their parent morpheme’s frequency and neighborhood density and will inherit different articulatory parameters as a result of being associated with morpheme-specific precompiled gestural scores. This leads to the second prediction made by the HPH, which is that those aspects of post-lexical processing that are influenced by lexical properties (e.g., duration, vowel space) will vary by morpheme across a multimorphemic word.

Taken together, the Heterogeneity of Processing Hypothesis makes the crucial prediction that, as a result of Morpheme Assembly and Segregated Lexical Inheritance, post-lexical processing will vary across a multimorphemic word. That is, the post-lexical processing of multimorphemic words is predicted to be heterogeneous.

To illustrate these predictions, consider the compound word sunshine (Figure 1). During retrieval, each morpheme will provide access to its constituent phonemes and associated articulatory plan, should one be stored. Since each morpheme has its own representation, binding processes must integrate them in some way: the segments from each morpheme will have to be bound together as will the separate articulatory plans (this binding is depicted graphically as grey bands). Further, since sun is far more frequent and has many more neighbors than shine, its phonemes will receive more activation, indicated in the diagram by darker borders. In contrast, consider the monomorphemic word carbine. Since its lexical representation consists of a single unit, its phonological
representation will be stored and activated together as a unit, both at segmental and articulatory planning levels. Further, all phonemes in the word will receive roughly the same levels of activation and the same articulatory parameters since they are all associated with the same lexical unit. As a result, post-lexical processing is predicted to be relatively heterogeneous for *sunshine* and relatively homogenous for *carbine*. 
Figure 1. Depiction of the processing of multi- and monomorphemic words predicted by the Heterogeneity of Processing Hypothesis. Panel A depicts the processing of the compound word *sunshine*. Dark borders around the segments in *sun* represent greater activation due to *sun*’s relatively high frequency and neighborhood density. Grey bands indicate the need to bind together the segmental and articulatory representations of each morpheme. Panel B depicts the processing of the monomorphemic word *carbine*. In both panels, dotted lines indicate the possibility that lexical representations provide access to stored articulatory representations.
Present Investigation

Study overview

The current study investigates the first prediction of the Heterogeneity of Processing Hypothesis, specifically, that post-lexical processes apply more weakly across morphemes than within. The investigation makes use of the phoneme similarity effect reported recently by Cohen-Goldberg (2012). In a regression analysis of oral reading reaction times, Cohen-Goldberg found that the phonological similarity of a word’s consonants slowed production latencies. For example, subjects took longer to begin uttering words like beep than weep, even after controlling for factors such as frequency, length, orthographic consistency, letter similarity, etc. This inhibitory effect of similarity was found for consonant pairs in onset clusters (trim), in the onset and coda (trim), and crucially, even for onset and suffix consonants in verbs suffixed with –ed (trimmed). For reasons that will be described below, Cohen-Goldberg concluded that the similarity effect stemmed from phoneme competition during production. According to this proposal, the phonemes within a word compete for selection during phonological encoding, with similar phonemes competing more strongly than dissimilar phonemes.

The phoneme similarity effect can thus serve as a diagnostic to determine which phonemes interact in the planning of a word’s phonological form, and to what extent. An inhibitory effect of similarity indicates that two phonemes are competing for selection or are otherwise inhibiting each other. The present study extends this approach to investigate the post-lexical processing of multimorphemic words. According to the HPH,
post-lexical processing is weaker across morpheme boundaries than within, which predicts that during phonological encoding, phonemes in different morphemes should compete with each other less strongly than phonemes from the same morpheme.

Three studies are reported. Study 1 investigated the generality of the phoneme similarity effect in multimorphemic words. Although Cohen-Goldberg (2012) found effects of root-suffix similarity in words suffixed with the past tense, it is possible that the past tense suffix, being a single phoneme that integrates into the same syllable as the root, constitutes a special case, and that similarity effects are not found in multimorphemic words more generally. To this end, Study 1 investigated whether the phoneme similarity effect can be found in the production of words with more typical suffixes, namely –ing and –er. Studies 2 and 3 then tested the prediction made by the HPH, which is that post-lexical processing is weaker across morpheme boundaries than within a single morpheme. Study 2 compared the strength of the phoneme similarity effect in words containing the suffix –ed to monomorphemic words ending in /d/ (e.g., bayed vs. bed). Study 3 compared the strength of the similarity effect in words suffixed with –y to monomorphemic words ending in /i/ (e.g., baby vs. flaky).

Methods

The methods used in the present analyses are identical to the methods used in Cohen-Goldberg (2012) and will be reviewed here. The data for the analyses were obtained from the English Lexicon Project (ELP), which collected oral reading latency times for over 40,000 English mono- and multimorphemic words (Balota, Yap, Cortese, Hutchison, Kessler, Loftis, Neely, Nelson, Simpson & Treiman, 2007). In that study,
words were presented one at a time in uppercase and naming latency was measured using a voice key. Only correct responses (as self-reported by the subjects) were included in the present analyses.

For the analyses reported here, all correct trials corresponding to the relevant words (e.g., words suffixed with –er) were retrieved from the ELP website. Linear mixed-effects models were used to analyze the data and were run with the lmer package (Bates, Maechler, & Dail, 2008) of the statistical package R. Each model contained 1) a set of control variables to control for factors known to affect oral reading processes 2) a set of random effects variables to allow the results to generalize to new subjects and items, and 3) the variables of interest (e.g., consonant similarity). The dependent variable in each was log naming latency in milliseconds. The control variables, which control for factors such as word frequency, length, neighborhood density, orthographic consistency, etc., were drawn from Baayen, Feldman & Schreuder (2006) for Studies 1 and 2 and Yap & Balota (2009) for Study 3. These variables were shown in these studies to significantly predict oral reading latencies in mono- and multisyllabic words, respectively. In addition to these variables, several other variables were included in order to control for various aspects of processing; these variables will be described in each study and are listed in Appendix A. In all analyses, a variable encoding the letter similarity of the critical letters (the letters whose corresponding sounds were of interest) was included. This variable was computed using the uppercase similarity norms of Boles and Clifford (1989) and was included to make sure that effects of phonological similarity were not due to letter similarity. Each model contained full random effects structure, with random intercepts.

http://elexicon.wustl.edu
for subjects and items and random slopes for the variables of interest (including interaction terms) for both subjects and items.

Consonant similarity was calculated using the feature-based metric proposed by Bailey and Hahn (2005). This measure defines similarity in terms of the number of features shared by two phonemes and ranges from 0-4 (Voicing, Place, Manner, Sonority). Similarity values for singleton consonants were obtained from the appendix of Bailey and Hahn (2005). In cases involving more than 2 consonants, similarity was calculated by averaging the similarity of all pairs. For example, the similarity of the onset and coda of the word _crowd_ was calculated by averaging SIM(/k/;/d/) and SIM(/r/;/d/). In Study 3, vowel transcriptions were obtained from the Hoosier Mental Lexicon (Nusbaum, Pisoni, & Davis, 1984) and vowel similarity was calculated using the features Height (values: high, mid, low), Backness (front, central, back), Rounding (round, unround), and Tenseness (tense, lax). Vowel similarity thus also ranged from 0-4.

Each analysis was performed the same way: log reaction times were first fit by the full model and data points with a standardized residual greater than ± 2.5 were considered outliers and removed. The model was then refit to the data and interpreted. Since it is not currently possible to calculate _p_-values for linear mixed-effects models (Baayen, Davidson, & Bates, 2008) and since Markov chain Monte Carlo simulations used to estimate _p_-values have not yet been implemented for models with random intercepts, model comparison was used to determine the significance of the variables of interest. Differences in the likelihood of nested models approximately follow a _χ^2_ distribution (Agresti, 2002), and so a significant chi-square test of these models indicates that the variable of interest significantly improved the fit of the model. Model comparisons were
used to test the significance of all variables of interest in the present studies. Tables containing the results of the analysis for each fixed effect are reported for each study.

Lastly, it should be noted that collinearity among the control variables was not controlled. Since beta weight, sign, and standard error estimates are only reliable when collinearity is minimal, the results for these variables are provided to facilitate interpretation of the models but should not be used to draw conclusions about them. Collinearity was always controlled for the variables of interest, however, making their estimates reliable.

*Suitability of oral reading latency data*

Before continuing, an important issue that must be addressed is whether oral reading is an appropriate task for investigating the phonological processing of multimorphemic words. One concern is that oral reading involves many different processes and as a result phonological effects may not necessarily reflect the processes involved in spoken production. Another concern is that oral reading can be accomplished in a sub-lexical manner and thus oral reading data may not necessarily reflect the processing of multimorphemic representations. Each of these concerns will be addressed here.

For oral reading reaction time data to be relevant to the theoretical questions of the present study, they must reflect how phonological representations are processed during spoken production and ideally should reflect a pre-articulatory stage of processing. Cohen-Goldberg (2012) reported three findings indicating that the phoneme similarity effect observed in the ELP data possesses just these properties. First, although Cohen-
Goldberg found significant effects of phonological similarity in oral reading reaction times, no such effects were found in an analysis of visual lexical decision reaction times. This suggests that although phonological representations may be generated during orthographic comprehension (e.g., Meyer, Schvaneveldt, & Ruddy, 1974; Rubenstein, Lewis, & Rubenstein, 1971) the phonological similarity effect observed in the oral reading data originates at a point in the reading process following orthographic and semantic processing, i.e., spoken production. Second, Cohen-Goldberg analyzed oral reading latencies of words suffixed with the past tense. Although in monosyllabic words the past tense suffix has two allomorphs—[t] and [d]—the regression models obtained a significantly better fit when the suffix was assumed to be [d]. This indicates that the similarity effect arises at a relatively early stage of phonological processing, before the final phonetic form of the suffix has been generated (e.g., during phonological encoding). Finally, for the similarity effect to be informative about the processes involved in spoken production, it is important to establish that it is truly a general component of speech planning and is not specific to the reading process. To this end, Cohen-Goldberg conducted an analysis of picture naming latencies and also found an inhibitory effect of consonant similarity. Together, these findings indicate that the oral reading reaction times analyzed in Cohen-Goldberg (2012) and used in the present investigation do in fact reflect general properties of post-lexical phonological processes and that the similarity effect is not merely an artifact of the reading process.

The second concern pertains to whether the oral reading data are at all informative about multimorphemic word processing. For this to be the case, it is essential that the subjects in the ELP study processed the morphologically complex stimuli as being truly
multimorphemic and not simply as a string of letters. Most theories of reading posit that there are two main ways in which words can be read aloud. Words can be read ‘lexically’, whereby the pronunciation of a known word/morpheme is retrieved from long-term memory and words can also be read ‘sub-lexically’, whereby the pronunciation of a word is assembled based on the common spelling-sound mappings of the language (e.g., TH → /θ/). According to these theories, morphologically complex words will only be processed as being multimorphemic if they are processed through the lexical pathway: the lexical route will process complex words in terms of their component morphemes while the sub-lexical route, which is hypothesized to only operate over graphemes, has no information about morphological structure and will treat morphologically complex words as simple letter strings. The concern then is that if subjects in the English Lexicon Project were to have read the morphologically complex words in a sub-lexical fashion, the words would have been processed as if they were monomorphemic and the resulting reaction time data would not be informative about the phonological processing of multimorphemic words.

Two factors suggest that the participants in the English Lexicon Project did in fact rely on lexical processing to read the morphologically complex words. The first relates to the fact that the pronunciation of many multimorphemic words is not transparent in the orthography. For example, the voicing of the plural suffix –s varies despite always being spelled with the letter S. The past tense suffix –ed undergoes similar voicing changes and is not pronounced with a vowel (in monosyllabic words) despite being spelled with the letter E. In other cases, the morphological structure of a word is essential to the proper parsing of letters into digraphs (without knowledge of the compound boundary, the word
pothole would be pronounced with a /θ/). Finally, suffixes such as –ese and –ity cause stress and vowel changes that are not marked in the orthography (Japán~Japanneese, mort[æ]l~mort[æ]lity). The sub-lexical reading procedure, since it relies on common orthography-phonology mappings, will not generate the correct pronunciation for any of these words (e.g., passed → *[pæs]d). Although we cannot independently verify the accuracy of the subjects’ responses (they were all self-reported as accurate), it is reasonable to assume that these words were in fact produced correctly, thus indicating that subjects were utilizing the lexical reading procedure.

The second factor relates to the fact that the experimental design used to collect the data for the ELP likely biased subjects to favor lexical over sub-lexical processing. It is known that the oral reading process can be biased by task context, causing subjects to favor or rely on one processing route over the other. For example, it has been found that reading a number of non-words in a row can cause subjects to favor sub-lexical processing while reading a number of orthographically irregular words can bias subjects in favor of lexical processing (e.g., Reynolds & Besner, 2005; Zevin & Balota, 2000).

Given that all of the words used in the ELP’s reading tasks were real words, and given the fact that the vast majority of these words were multimorphemic, irregularly spelled, or both, it seems likely that responses were dominated by lexical processing. Putting all of these considerations together, it seems likely that the reaction time data analyzed here reflect post-semantic, pre-articulatory processes acting over lexically generated morphological representations, making them suitable for examining how multimorphemic words are produced in normal speech.
Study 1

In order to test the generality of the cross-morpheme phoneme similarity effect described in Cohen-Goldberg (2012), oral reading reaction times for words suffixed with \(-ing\) and \(-er\) were analyzed. These suffixes were chosen based on their representation in the English Lexicon Project—both were found in over 300 word types, ensuring sufficient power for the analysis. Other affixes were judged to appear in too few word types and trials to provide sufficient power: \(un\)--: 77 word types; \(re\)--: 56; \(-ly\): 186; \(-ness\): 98; \(-less\): 130; \(-ful\): 77). Similarity was calculated for the root-final consonant and suffix consonant. For example, for the word baking, the similarity of /k/ and /ŋ/ was used; for the word baker, the similarity of /k/ and /r/ was used. To ensure that the effects of similarity were not due to competition among the phonemes of the root (e.g., /b/ and /k/ in baker), variables encoding the letter and phoneme similarity of these consonants were included in the model.

Results

Separate analyses were conducted for the \(-ing\) and \(-er\) datasets. After outliers were removed, the \(-ing\) dataset consisted of 21,897 trials from 831 words (457 trials were removed as outliers). The similarity of the root coda and suffix consonant was found to have an inhibitory effect on reaction times \((\beta = .011; \text{s.e.} = .002; t = 4.6; \chi^2(1) = 21.0, p < .00001)\). Since Root Coda-Suffix Similarity was correlated with Root Coda-Suffix Letter Similarity \((r = -0.585)\), the former was residualized against the latter and the analysis was rerun. The residualized predictor was still found to be inhibitory, confirming the stability of the effect in the model \((\beta = .011; \text{s.e.} = .002; t = 4.6)\).
After outliers were removed, the –er dataset consisted of 8554 trials from 327 words (185 trials were removed in this fashion). The similarity of the root coda and suffix consonant was found to have a significant inhibitory effect on reaction times ($\beta = .016$; s.e. = .004; $t = 3.9$; $\chi^2(1) = 15.6, p < .0001$), an effect that persisted once root coda-suffix similarity was regressed against two predictors with which it was moderately correlated (Consistency PC2: $r = .31$; Root Coda-Suffix Letter Similarity: $r = .38$) and reentered into the model ($\beta = .016$; s.e. = .004; $t = 3.9$). The results of the –ing and –er analyses are provided in Table 1 and Table 2, respectively.

In order to be sure that these effects were truly related to phonological similarity and not due to the processing of repeated letters (Schoonbaert & Grainger, 2004), words containing identical letters in the relevant positions were removed. For the –ing analysis, all words containing root-final letters N, G, and NG were removed, resulting in the removal of 83 words and 2158 trials. For the –er analysis, all words containing root-final R were removed (e.g., bearer), resulting in the exclusion of 4 words and 90 trials. The models were refit and significant inhibitory effects were again found for both suffixes (–ing: $\beta = .010$; s.e. = .003; $t = 4.1$; $\chi^2(1) = 17.1, p < .0001$; –er: $\beta = .016$; s.e. = .005; $t = 3.5$; $\chi^2(1) = 13.1, p < .001$). This confirms that the effect is truly related to phonological similarity and not simply the existence of repeated letters.

Summary

The effect of phoneme similarity across morpheme boundaries was investigated in words suffixed with –ing and –er. In both cases, similarity had a significant inhibitory effect on reaction times. These results replicate and extend the findings of Cohen-
Goldberg (2012), confirming that phonemes in different morphemes interact with each other during phonological processing.

Table 1 Result summary: coefficient estimates $\beta$, standard errors $\text{SE}(\beta)$, and $t$-values for all predictors in the Study 1 analysis of words suffixed with $-ing$.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coeff. $\beta$</th>
<th>SE($\beta$)</th>
<th>$t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>6.544</td>
<td>0.051</td>
<td>128.2</td>
</tr>
<tr>
<td>Initial Segment Frication-Frication</td>
<td>0.044</td>
<td>0.005</td>
<td>8.7</td>
</tr>
<tr>
<td>Initial Segment Frication-Short</td>
<td>-0.005</td>
<td>0.006</td>
<td>-0.8</td>
</tr>
<tr>
<td>Initial Segment Voicing-Voiceless</td>
<td>0.020</td>
<td>0.006</td>
<td>3.3</td>
</tr>
<tr>
<td>FrequencyInitialDiphoneSyllable</td>
<td>0.006</td>
<td>0.001</td>
<td>4.3</td>
</tr>
<tr>
<td>FrequencyInitialDiphone</td>
<td>-0.017</td>
<td>0.003</td>
<td>-5.3</td>
</tr>
<tr>
<td>Root Consistency PC1</td>
<td>0.000</td>
<td>0.001</td>
<td>-0.4</td>
</tr>
<tr>
<td>Root Consistency PC2</td>
<td>-0.006</td>
<td>0.001</td>
<td>-4.1</td>
</tr>
<tr>
<td>Root Consistency PC3</td>
<td>-0.015</td>
<td>0.003</td>
<td>-4.8</td>
</tr>
<tr>
<td>Root Log Frequency</td>
<td>-0.005</td>
<td>0.002</td>
<td>-2.8</td>
</tr>
<tr>
<td>Root Written-Spoken Frequency Ratio</td>
<td>-0.002</td>
<td>0.002</td>
<td>-0.9</td>
</tr>
<tr>
<td>Root Orthographic Neighborhood Density</td>
<td>0.001</td>
<td>0.001</td>
<td>1.5</td>
</tr>
<tr>
<td>Root Inflectional Entropy</td>
<td>-0.010</td>
<td>0.006</td>
<td>-1.6</td>
</tr>
<tr>
<td>Word Root Log Frequency</td>
<td>-0.017</td>
<td>0.002</td>
<td>-10.3</td>
</tr>
<tr>
<td>Word Orthographic Neighborhood Density</td>
<td>-0.002</td>
<td>0.001</td>
<td>-2.0</td>
</tr>
<tr>
<td>Word Letter Length</td>
<td>0.016</td>
<td>0.004</td>
<td>4.3</td>
</tr>
<tr>
<td>Root Onset-Coda Letter Similarity</td>
<td>0.015</td>
<td>0.004</td>
<td>3.5</td>
</tr>
<tr>
<td>Root Onset-Coda Phoneme Similarity</td>
<td>0.007</td>
<td>0.002</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Table 2 Result summary: coefficient estimates $\beta$, standard errors SE($\beta$), and $t$-values for all predictors in the Study 1 analysis of words suffixed with $-er$.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coeff. $\beta$</th>
<th>SE($\beta$)</th>
<th>$t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>6.383</td>
<td>0.063</td>
<td>102.0</td>
</tr>
<tr>
<td>Initial Segment Frication-Frication</td>
<td>0.034</td>
<td>0.008</td>
<td>4.2</td>
</tr>
<tr>
<td>Initial Segment Frication-Short</td>
<td>-0.005</td>
<td>0.010</td>
<td>-0.5</td>
</tr>
<tr>
<td>Initial Segment Voicing-Voiceless</td>
<td>0.017</td>
<td>0.009</td>
<td>1.8</td>
</tr>
<tr>
<td>FrequencyInitialDiphoneSyllable</td>
<td>0.011</td>
<td>0.003</td>
<td>4.4</td>
</tr>
<tr>
<td>FrequencyInitialDiphone</td>
<td>-0.003</td>
<td>0.003</td>
<td>-1.0</td>
</tr>
<tr>
<td>Root Consistency PC1</td>
<td>-0.001</td>
<td>0.002</td>
<td>-0.6</td>
</tr>
<tr>
<td>Root Consistency PC2</td>
<td>-0.006</td>
<td>0.002</td>
<td>-2.6</td>
</tr>
<tr>
<td>Root Consistency PC3</td>
<td>-0.001</td>
<td>0.002</td>
<td>-0.2</td>
</tr>
<tr>
<td>Root Log Frequency</td>
<td>-0.006</td>
<td>0.002</td>
<td>-2.7</td>
</tr>
<tr>
<td>Root Written-Spoken Frequency Ratio</td>
<td>0.008</td>
<td>0.003</td>
<td>2.3</td>
</tr>
<tr>
<td>Root Orthographic Neighborhood Density</td>
<td>0.000</td>
<td>0.001</td>
<td>-0.1</td>
</tr>
<tr>
<td>Root Inflectional Entropy</td>
<td>-0.016</td>
<td>0.008</td>
<td>-2.1</td>
</tr>
<tr>
<td>Word Log Frequency</td>
<td>-0.013</td>
<td>0.002</td>
<td>-7.1</td>
</tr>
<tr>
<td>Word Orthographic Neighborhood Density</td>
<td>0.001</td>
<td>0.002</td>
<td>0.4</td>
</tr>
<tr>
<td>Word Letter Length</td>
<td>0.020</td>
<td>0.006</td>
<td>3.3</td>
</tr>
<tr>
<td>Root Onset-Coda Letter Similarity</td>
<td>-0.005</td>
<td>0.007</td>
<td>-0.7</td>
</tr>
</tbody>
</table>
### Study 2

Having shown in Study 1 that phonemes from different morphemes compete with each other during phonological processing, the strength of this competition within and across morphemes was investigated in Study 2. A key prediction of the Heterogeneity of Processing hypothesis is that post-lexical processing is weaker across morphemes than within due to the need to bind together representations from different morphemes. This means that phoneme competition—indexed by the inhibitory effect of phoneme similarity—should be weaker for pairs of phonemes in different morphemes than for pairs within the same morpheme. To test this prediction, the similarity effect was compared in words suffixed with *–ed* to the effect in monomorphemic words ending in */d/.*

All monomorphemic monosyllabic words ending in */d/.* were extracted from the ELP as were all monosyllabic bimorphemic words containing the suffix *–ed*. To ensure that the mono- and multimorphemic words had similar syllabic structure, only words with a VC rhyme structure were included in the analysis. This meant that all monomorphemic words contained a single coda consonant (e.g., *crowd, bread, slide*) while all suffixed words consisted of a vowel-final root plus the past-tense suffix (e.g., *glowed, tied, weighed*). This criterion also ensured that the past-tense morpheme was always

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root Onset-Coda Phoneme Similarity</td>
<td>0.001</td>
<td>0.004</td>
<td>0.4</td>
</tr>
<tr>
<td>Root Coda-Suffix Letter Similarity</td>
<td>-0.003</td>
<td>0.007</td>
<td>-0.4</td>
</tr>
<tr>
<td>Root Coda-Suffix Phoneme Similarity (residualized)</td>
<td>0.016</td>
<td>0.004</td>
<td>3.9</td>
</tr>
</tbody>
</table>
expressed as the /d/ allomorph. The multimorphemic words in this set were found to be slightly but significantly longer by phoneme than the monomorphemic words (mean length mono: 3.43; multi: 3.55; \( t(3703) = -5.73, p < .0001 \)). Analyses indicated that if all trials of the 3 multimorphemic words containing 3 onset consonants (screwed, sprayed, strayed) were removed, the two sets would not differ in length (mono: 3.43, multi: 3.44; \( t(3626) = -0.33; p = .74 \)). To ensure the generalizability of the results, the analyses were run with and without these words.

For this analysis, the model consisted of the baseline control variables as well as the following variables of interest: Number of Morphemes, Onset-Coda Phoneme Similarity (range: 1-4), and the interaction term Onset-Coda Phoneme Similarity x Number of Morphemes (see Appendix for all of the variables included in the model). To facilitate interpretation, Number of Morphemes was contrast coded (one morpheme = -1, two morphemes = 1) and Onset-Coda Phoneme Similarity was centered (centered range: -1.4–2.8). The model also contained the interaction term as a random slope for both subjects and items (the model failed to converge when similarity and number of morphemes were also included, so it was decided to remove them in favor of the interaction term).

Following the removal of 84 outliers, the dataset consisted of 2586 monomorphemic trials (from 99 word types) and 1035 multimorphemic trials (from 42 types). The regression analysis revealed a significant inhibitory effect of phoneme similarity (\( \beta = .020; \text{s.e.} = .075; t = 2.7; \chi^2(1) = 8.1, p < .01 \)) and a trend for an inhibitory effect of the number of morphemes (\( \beta = .013; \text{s.e.} = .008; t = 1.7; \chi^2(1) = 3.1, p = .08 \)). Crucially, the effect of phoneme similarity interacted with number of morphemes (\( \beta = -\)).
.017; s.e. = .006; \( t = -3.0 \); \( \chi^2(1) = 9.8, p < .01 \), with the effect of similarity diminishing in the suffixed words relative to monomorphemic words (the results of this analysis are presented in Table 3). The interaction term was still significant when the suffixed words containing 3 onset consonants were excluded (\( \beta = -.017; \) s.e. = .006; \( t = -2.9; \) \( \chi^2(1) = 9.3, p < .01 \)). Figure 2 presents a graph of the interaction effect. In this figure, Number of Morphemes (centered) is on the x-axis, the various levels of Onset-Coda Similarity (centered) are represented by the various dashed lines, and raw RT in milliseconds is on the y-axis (the log transformation used in the analysis was undone in the graph to facilitate interpretation). The changing spread of the similarity variable depicts how the effect of similarity on RT differs in mono- and multimorphemic words.

A couple of measures were taken to rule out possible confounds in this analysis. First, to ensure that the effect of similarity was not being driven by the inhibitory effect of processing repeated letters (Schoonbaert & Grainger, 2004), all words containing an initial letter D (e.g., dread, died) were removed and the analysis was rerun. The interaction was still found to be significant (\( \beta = -.018; \) s.e. = .006; \( t = -3.3; \) \( \chi^2(1) = 11.6, p < .001 \)), indicating that the effect is truly related to phonological similarity. Second, it was observed that long and short vowels were not equally distributed across the two groups of words. All of the multimorphemic words contained a long vowel while the monomorphemic words contained both short and long vowels. If the strength of the phoneme similarity effect is influenced by the length of the vowel, this numerical imbalance could lead to a weaker effect of similarity in the multimorphemic words. An analysis conducted on the monomorphemic words found that vowel length did not influence reaction times (Vowel Length: \( \beta = .004; \) s.e. = .005; \( t = 0.7; \) \( \chi^2(1) = 0.4, p = .5 \))
and did not interact with phoneme similarity (Onset-Coda Phoneme Similarity x Vowel Length: $\beta = .001; \text{s.e.} = .004; t = 0.3; \chi^2(1) = .1, p = .8$), ruling it out as a confound in the overall analysis.

**Summary**

The post-lexical processing of multimorphemic words was investigated by comparing the inhibitory effect of phoneme similarity in suffixed words relative to form-matched monomorphemic words. A significant effect of similarity was found, indicating that phonemes from the same and different morphemes compete with each other during phonological encoding. The similarity effect was reduced when the final phoneme corresponded to the past tense suffix, suggesting that phonemes in different morphemes do not compete as strongly with each other as phonemes located within the same morpheme. These results support the Heterogeneity of Processing Hypothesis.
Figure 2. Results of Study 2. Number of Morphemes (centered values: -1, 1) is depicted on the x-axis while Phoneme Similarity (centered values: -1.37–2.79) is represented by the dashed lines (raw RT is on the y-axes). The interaction between phoneme similarity and number of morphemes is illustrated by the change in the spread of the lines: the effect on RT is larger in monomorphemic words (coded as Number of Morphemes = -1) than disyllabic words (coded as Number of Morphemes = 1).

Table 3 Result summary: coefficient estimates $\beta$, standard errors SE($\beta$), and t-values for all predictors in the Study 2 analysis of words suffixed with –ed and monomorphemic words ending in /d/.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coeff. $\beta$</th>
<th>SE($\beta$)</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>6.509</td>
<td>0.073</td>
<td>89.2</td>
</tr>
<tr>
<td>Initial Segment Frication-Frication</td>
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<td>0.012</td>
<td>6.1</td>
</tr>
<tr>
<td>Variable</td>
<td>Mean 1</td>
<td>Mean 2</td>
<td>t</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>--------</td>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>Initial Segment Frication-Short</td>
<td>0.066</td>
<td>0.018</td>
<td>3.7</td>
</tr>
<tr>
<td>Initial Segment Voicing-Voiceless</td>
<td>0.064</td>
<td>0.014</td>
<td>4.6</td>
</tr>
<tr>
<td>FrequencyInitialDiphoneSyllable</td>
<td>0.004</td>
<td>0.004</td>
<td>1.0</td>
</tr>
<tr>
<td>FrequencyInitialDiphone</td>
<td>-0.011</td>
<td>0.004</td>
<td>-2.4</td>
</tr>
<tr>
<td>Root Consistency PC1</td>
<td>0.001</td>
<td>0.003</td>
<td>0.3</td>
</tr>
<tr>
<td>Root Consistency PC2</td>
<td>0.007</td>
<td>0.003</td>
<td>2.2</td>
</tr>
<tr>
<td>Root Consistency PC3</td>
<td>0.003</td>
<td>0.003</td>
<td>1.2</td>
</tr>
<tr>
<td>Root Log Frequency</td>
<td>-0.008</td>
<td>0.004</td>
<td>-2.1</td>
</tr>
<tr>
<td>Root Written-Spoken Frequency Ratio</td>
<td>-0.002</td>
<td>0.004</td>
<td>-0.6</td>
</tr>
<tr>
<td>Root Orthographic Neighborhood Density</td>
<td>-0.001</td>
<td>0.002</td>
<td>-0.6</td>
</tr>
<tr>
<td>Root Inflectional Entropy</td>
<td>-0.017</td>
<td>0.008</td>
<td>-2.2</td>
</tr>
<tr>
<td>Word Log Frequency</td>
<td>-0.011</td>
<td>0.003</td>
<td>-3.1</td>
</tr>
<tr>
<td>Word Orthographic Neighborhood Density</td>
<td>0.002</td>
<td>0.002</td>
<td>0.8</td>
</tr>
<tr>
<td>Word Letter Length</td>
<td>0.026</td>
<td>0.009</td>
<td>3.0</td>
</tr>
<tr>
<td>Onset-Coda Letter Similarity</td>
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<td>0.012</td>
<td>-1.2</td>
</tr>
<tr>
<td>Onset-Coda Phoneme Similarity (centered)</td>
<td>0.020</td>
<td>0.007</td>
<td>2.7</td>
</tr>
<tr>
<td>Number of Morphemes (centered)</td>
<td>0.013</td>
<td>0.008</td>
<td>1.7</td>
</tr>
<tr>
<td>Onset-Coda Phoneme Similarity x</td>
<td>0.017</td>
<td>0.006</td>
<td>2.9</td>
</tr>
</tbody>
</table>

**Study 3**

As a follow-up to Study 2, the strength of the phoneme similarity effect was
evaluated in words ending in the adjective-forming suffix –y and monomorphemic words ending in /i/. This dataset provides an opportunity to test the generalizability of the cross-boundary weakening observed in Study 2: the analysis involves a different suffix, a different syllable structure (disyllabic words), a different similarity metric (vowel similarity), and a different set of regression variables (to accommodate the visual processing of disyllabic words).

All disyllabic words ending in /i/ were extracted from the English Lexicon Project. Words containing the diphthongs /aɪ/, /oɪ/, and /aʊ/ were excluded, as were words with r-colored vowels. Words were classified as either monomorphemic or containing the adjective-forming suffix –y. Words that could be construed as containing a bound root (e.g., silly, happy, burly) were categorized as monomorphemic. Since the effect of vowel similarity is likely to diminish with distance, only words containing a single phonological consonant between the two vowels were included in the analysis (e.g., body, soapy).

The variables used in the analysis were based on the work of Yap and Balota (2009), who investigated the factors that influence the processing of multisyllabic words. Since not all of the variables that Yap and Balota found to be significant predictors of oral reading reaction times have been collected for multimorphemic words, a subset of their predictors were included in this analysis. In addition to these variables, two variables encoding properties of the root word were included (root frequency and root orthographic neighborhood density) as was a variable encoding the similarity of the

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4 Preliminary analyses investigating whether these words behave as if they contain the suffix –y, despite containing a bound root, were inconclusive. As such, they were treated as monomorphemic.
vowel letters (e.g., the similarity of OA and Y for soapy). Vowel similarity was calculated using the procedure described in the methods section above. The full set of variables is provided in Appendix A.

Following the removal of 176 outlier trials, the dataset consisted of 3698 monomorphemic trials (147 types) and 4114 multimorphemic trials (159 types). The analysis found a marginal inhibitory effect of vowel similarity ($\beta = .007; \text{s.e.} = .004; t = 1.9; \chi^2(1) = 3.6; p = .056$) and a significant advantage for multimorphemic words relative to monomorphemic words ($\beta = -.015; \text{s.e.} = .005; t = -2.9; \chi^2(1) = 8.0; p < .01$). The interaction between similarity and number of morphemes came close to but did not reach significance, with the effect of similarity diminishing in multimorphemic words ($\beta = -.006; \text{s.e.} = .004; t = -1.7; \chi^2(1) = 3.1; p = .076$). A summary of the results can be found in Table 4.

**Summary**

The results of Study 3 broadly support the Heterogeneity of Processing hypothesis. A marginal inhibitory effect of vowel similarity was found, suggesting that vowels compete for selection during phonological encoding in much the same way as consonants, as was a significant facilitatory effect of morphological structure.

At the moment, it is unclear why the effect of similarity is weaker here than the effect of similarity observed for consonants in Study 2. Shattuck-Hufnagel (1986) reports that spontaneous speech errors involving vowels occur less frequently than errors involving consonants, suggesting that vowels may not compete with each other as strongly during phonological encoding as do consonants. Another possibility is that
segment competition decreases across syllable boundaries, causing the vowels analyzed in here to interact with each other more weakly than the consonants analyzed in Study 2.

Crucially, a facilitatory interaction between vowel similarity and number of morphemes was found that approached significance, suggesting that competition between phonemes is reduced across the morpheme boundary. These results are broadly similar to those observed in Study 2 and thus provide some support for the notion that morphological boundaries act as processing boundaries in spoken production. Phonological processing, indexed here by vowel competition, appears to be weaker across morphemes than within.

### Table 4 Result summary: coefficient estimates $\beta$, standard errors SE(\(\beta\)), and $t$-values for all predictors in the Study 3 analysis of words suffixed with –\(y\) and monomorphemic words ending in /i/.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coeff. $\beta$</th>
<th>SE((\beta))</th>
<th>$t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>6.718</td>
<td>0.076</td>
<td>88.2</td>
</tr>
<tr>
<td>Initial Segment Voicing</td>
<td>-0.009</td>
<td>0.005</td>
<td>-1.8</td>
</tr>
<tr>
<td>Initial Segment Frication</td>
<td>0.038</td>
<td>0.008</td>
<td>4.5</td>
</tr>
<tr>
<td>Syl1 Onset FF Consistency</td>
<td>-0.056</td>
<td>0.026</td>
<td>-2.1</td>
</tr>
<tr>
<td>Syl1 Rhyme FF Consistency</td>
<td>0.005</td>
<td>0.016</td>
<td>0.3</td>
</tr>
<tr>
<td>Syl2 Onset FF Consistency</td>
<td>-0.029</td>
<td>0.018</td>
<td>-1.7</td>
</tr>
<tr>
<td>Syl2 Rhyme FF Consistency</td>
<td>-0.209</td>
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<td>-3.4</td>
</tr>
<tr>
<td>Syl1 Onset FB Consistency</td>
<td>-0.068</td>
<td>0.023</td>
<td>-3.0</td>
</tr>
<tr>
<td>Syl1 Rhyme FB Consistency</td>
<td>0.004</td>
<td>0.013</td>
<td>0.3</td>
</tr>
<tr>
<td>Syl2 Onset FB Consistency</td>
<td>0.052</td>
<td>0.017</td>
<td>3.0</td>
</tr>
</tbody>
</table>
### General Discussion

In this paper, the character of post-lexical processing for multimorphemic words was considered. Drawing on findings from the linguistic and psycholinguistic literature showing that 1) multimorphemic words are represented in terms of their component morphemes at lexical levels, 2) have structural weaknesses at morpheme boundaries in their post-lexical representations, and the fact that 3) post-lexical processes are influenced by lexical properties, the Heterogeneity of Processing Hypothesis was proposed which predicts that post-lexical processing is heterogeneous across a multimorphemic word. In particular, post-lexical processing is predicted to be 1) weaker for heteromorphemic than tautomorphemic sequences and 2) to vary according to each morpheme’s lexical properties.
The first prediction was tested by comparing the strength of phoneme competition during phonological encoding across and within morphemes. Analyses of oral reading latencies showed that phoneme competition—as indexed by an inhibitory effect of phoneme similarity—was significantly weaker in words suffixed with –ed compared to matched monomorphemic words ending in /d/. An analysis of words suffixed with –y showed a similar pattern that approached significance. These results indicate that phonological encoding, the stage when phonemes are retrieved, selected, and ordered, applies more weakly for heteromorphemic than tautomorphemic phonemes, providing support for the HPH.

The status of affixes in spoken production

In an examination of words suffixed with –ed, Cohen-Goldberg (2012) reported significant effects of onset-suffix similarity on oral reading reaction times, suggesting that root and suffix phonemes compete with each other during post-lexical processing. The present study replicated these findings (Study 1: –er, –ing) and demonstrated that this competition is weaker than the competition that occurs among root phonemes (Study 2: –ed, Study 3: –y). One question these results raise is: what is the strength of root-suffix phoneme competition? Although significant effects of onset-suffix similarity were found in Study 4 of Cohen-Goldberg (2012) and Study 1 here, inspection of the beta weights for the interaction terms in Studies 2 and 3 (see Tables 3 and 4 above) suggest that the effect of similarity is nearly or completely diminished in multimorphemic words. The clearest comparison is Cohen-Goldberg’s Study 4 and Study 2 of the present investigation, which both examined competition in words suffixed with –ed. Although it
is possible that Study 2 represents a failure to replicate the heteromorphemic similarity effect, what seems more likely is that cross-boundary competition occurs but is rather weak and requires a large number of trials to observe. Cohen-Goldberg’s study, which found a significant effect of onset-suffix similarity, consisted of 15,896 trials from 620 words while in the present work, Study 2 contained 1035 trials from 42 words. Future work should attempt to quantify the size of the competition effect within and across morphemes (and across different affixes) using sufficiently large datasets.

While the reduction in the phoneme similarity effect observed in Studies 2 and 3 is consistent with the claim that post-lexical processes are weaker when applying across suffix boundaries, it is important to consider an alternative possibility which is that the suffix phonemes may simply have had less activation—and thus competed more weakly—than the equivalent non-morphemic phonemes.

Although it is not possible at this time to definitively say one way or another, there is some evidence that affix phonemes are not weaker than root phonemes and may in some ways have a more robust representation at post-lexical stages of processing. First, although /t/ and /d/ are frequently deleted in word-final position in English, especially when followed by another consonant, it has been found that this deletion process is less likely to occur when the final segment corresponds to the past-tense suffix –ed than non-morphemic /t/ and /d/ (e.g., Neu, 1980; Roberts, 1997). Furthermore, it has been shown in the laboratory that the plural and past tense suffixes are pronounced with greater duration than their non-morphemic counterparts (Losiewicz, 1995; Schwarzlose & Bradlow, 2001; Walsh & Parker, 1983). Finally, work by Kuperman et al. (2007) on Dutch interfixes suggests that affixes may receive paradigmatic support from the lexicon,
increasing the robustness of their representation and the duration of their phonetic realization. It thus seems reasonable to conclude that the suffix phonemes examined in the present investigation were not weaker—and in fact may be stronger from a phonological perspective—than the latter.

Towards a functionalist theory of morphophonology

The fact that phonemes interact with each more weakly when in different morphemes may be important in accounting for a number of morphophonological phenomena in the world’s languages. It has been noted that there is a cross-linguistic tendency for phonological complexity to correlate with morphological productivity: words with productive morphology often contain marked phonological sequences (Burzio, 2002; Carlson & Gerfen, 2011; Hay & Baayen, 2003; Zuraw, 2009). One example of this general organization may be seen in Turkish vowel harmony: while vowels in root-suffix combinations must harmonize, the vowels in compounds do not. Similarly in English, although geminates are banned from monomorphemic words (*spaghe[tt]i) and words containing less productive suffixes (e.g., in-: i[n]umerable, *i[nn]umerable), they are allowed in words containing more productive affixes and compounds (e.g., un-: u[nn]ecessary; boo[kk]eeper).

This pattern has played a pivotal role in some theories of phonological grammar, primarily the theory of Lexical Phonology and Morphology proposed by Kiparsky (1982) and Monahan (1982). Although a review of this theory is beyond the scope of this paper, the critical element for present purposes is that productive morphology is assumed to form a lexical stratum (‘Level 2’ morphology) that is subject to fewer phonological rules
than a stratum containing less productive morphology (‘Level 1’). This organization caused certain phonological rules affecting less productive morphology to be absent in productive morphology (e.g., degemination). While this organization furnished the theory with *descriptive adequacy*, it crucially failed to provide it with *explanatory adequacy*—the correlation between morphological productivity and phonological inertness was merely stipulated and not derived from more basic principles.

The heterogeneous quality of post-lexical processing argued for here may provide part of a functional explanation for this correlation. While the origin of phonological grammars remains hotly debated, there is growing belief that many phonological rules derive from phonetically-motivated sound patterns (e.g., Blevins, 2004). For example, it has been claimed that vowel harmony rules arise when phonetic vowel-to-vowel coarticulation becomes learned as a phonological process (e.g., Benguerel & Cowan, 1974; Bell-Berti & Harris, 1979; Purcell, 1979; Fowler, 1981). In multimorphemic words, the fact that post-lexical processes apply more weakly across morphemes than within may serve to resist to some degree the types of phonetic changes that seed grammatical rules. For example, vowel-to-vowel coarticulation may be reduced across compound boundaries, producing fewer phonetic traces that could be grammaticalized into a compound vowel harmony rule. The fact that each morpheme has somewhat different phonetic properties (e.g., different degrees of vowel space expansion) as a result of different levels of cascading activation and differences in stored motor plans may further disrupt these diachronic processes. In contrast, a disyllabic monomorphemic word, which constitutes a homogenous domain for post-lexical phonological processes, receives far more consistent levels of activation, and is associated with a single motor
plan, is likely to be more vulnerable to these sorts of phonetic processes and as a result, a
more likely target for grammatical rules.5

The results in Study 2 suggest a similar effect may be behind the distribution of
geminates in English mono- and multimorphemic words. The inhibitory effect that
consonant competition exerts in production has been proposed to be one of the factors
that may lead to the various ‘Obligatory Contour Principle’ bans that languages have on
similar and geminate consonants within morphemes (Berg, 1998; Cohen-Goldberg, 2012;
Frisch, 2004). The fact that competition is reduced across morpheme boundaries, as
demonstrated in Study 2, suggests that this functional pressure is eased in productively
formed words (the effect of similarity has a less deleterious effect in processing) and
perhaps contributes to the appearance and tolerance of geminates in English productive
morphology.

_Lexicalization_

A similar process, but in reverse, may be behind morphophonological patterns
relating to _lexicalization_, the process by which historically morphologically complex
words come to be represented by a single morpheme. The lexicalization process is
frequently accompanied by shifts towards monomorphemic phonology (e.g., Brinton, &
Traugott, 2005). For example, the word _cupboard_ diachronically underwent the
phonological change [kʌp.ərd] → [kʌ.ərd]. The original pronunciation contains
phonology that is only found in compounds (adjacent syllables that bear stress, adjacent
stop consonants that disagree in voicing) while the contemporary pronunciation has

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5 This analysis bears some similarity to, and indeed may provide a functional explanation
for, output-output theories of the phonological grammar (Benua, 1997; Burzio, 1994).
eliminated these patterns in favor of those found in monomorphemic words (trochaic stress, no voicing disagreement in adjacent stops). Initially, the influence of having two distinct roots in the lexical representation (cup, board) may have weakened the phonological constraints that would have otherwise repaired its form (e.g., the sequence /pb/). As the meaning of the word drifted, however, the representation may have shifted from comprising multiple lexical representations to consisting of a single unit, thereby increasing the strength of post-lexical processes across the word. This would have led, over time, to the word taking on a more monomorphemic phonological profile.

The Heterogeneity of Processing hypothesis thus may provide a processing account of lexicalization and of lexical strata. Lexicalization (and shifts from later to earlier lexical strata, e.g., Level 2 to Level 1) could be defined at lexical levels as the shift towards unitary lexical representations and at post-lexical stages as the homogenization of processing. As phonological representations across morphemes become more unitary and as variation in activation levels are reduced, post-lexical processing may become increasingly homogenous. Cross-boundary interaction should increase—phonemes in different morphemes will have a stronger influence on each other’s pronunciation—and phonemes across the word should come to inherit increasingly similar levels of activation and articulatory parameters.

**Future directions**

The work reported here constitutes an important but preliminary step towards understanding the post-lexical processing of multimorphemic words. More work is needed to confirm the results reported here, ideally using other post-lexical processes.
(e.g., coarticulation). The second prediction of the HPH—that processing will vary across a multimorphemic word as a function of each morpheme’s lexical properties—similarly needs to be investigated.

On the theoretical side, the HPH needs to be elaborated to account for how post-lexical processing occurs when multimorphemic words have whole-word representations in addition to their morpheme-based representations. The exact direction this elaboration will take will depend in part on lexical theories of morphological processing. The simplest case is if whole-word representations compete with morpheme-based representations in a horse race, with only one or the other being used to access post-lexical representations. For example, both <afternoon> and <after>+<noon> may exist as lexical representations for afternoon in the phonological output lexicon but at any given time, only one is utilized to produce the word. In this case, the morpheme-based representation would be processed as described by the HPH above while the whole-word representation would likely be processed (more) similarly to a monomorphemic word. A more complex situation is if whole-word and morpheme-based representations both contribute in the processing of a word. This could happen if a whole-word lexical representation provides access to its component morphemes (<afternoon> → <after>+<noon>) or if both representations compete for selection and send cascading activation to post-lexical levels. In this case, the strength of the morpheme boundary and the exact lexical properties inherited by phoneme may be a blend of the two representations (e.g., Hay, 2003).

One promising outcome of this program of research is that the HPH, should it find support, could potentially serve as a linking hypothesis allowing post-lexical processing
data to be used to inform theories of lexical processing. To date, nearly all studies examining the lexical structure of morphologically complex words have utilized tasks thought to tap into lexical stages of processing (e.g., examining the effect of morpheme frequency on reaction times). The HPH, however, since it explicitly links lexical and post-lexical processing, may allow inferences about lexical processing to be made on the basis of post-lexical data. If the second claim of the HPH (that phonemes inherit the lexical properties of their parent morpheme) can be verified, for example, it could be used to adjudicate between morpheme-based and whole-word theories of lexical representation. If morphologically complex words are represented in terms of their component morphemes, each root in a compound should have different phonetic qualities that correlate with each root’s lexical properties. If morphologically complex words are instead represented by a single lexical unit (e.g., Caramazza, 1997), each root should have the same phonetic qualities and these qualities should correlate with the lexical properties of the entire word.

Another extension of the theory would be in the investigation of gradient theories of morphological processing. Although the discussion of lexical representation in the Introduction was cast in terms of a binary word-based/morpheme-based distinction, recent theories have argued that the distinction between morpheme- and word-based representations is gradient, rather than categorical. Some approaches have suggested that morphemes can be joined together with different strengths (Hay, 2003) while others have suggested that a variety of factors, including each morpheme’s paradigmatic/information theoretic support from the lexicon will affect a word’s structure (e.g., Kuperman, Betram & Baayen, 2008, 2010; Moscoso del Prado Martín, Kostić, & Baayen, 2004). Apart from
Hay’s (2003) study discussed in the Introduction, the consequences of this structure on post-lexical processing have not yet been investigated. It seems likely that the HPH could be extended fairly straightforwardly to make predictions for gradient structure (e.g., some words have stronger cross-boundary processing than others) and investigation along these lines could not only shed light on the influence of gradient lexical structure on post-lexical processing but potentially provide a point of converging evidence for gradient theories of morphology.
### Appendix A Fixed-effects variables used in the regression analyses.

<table>
<thead>
<tr>
<th>Study 1</th>
<th>Study 2</th>
<th>Study 3</th>
</tr>
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<tbody>
<tr>
<td>Initial Segment Frication</td>
<td>Initial Segment Voicing</td>
<td>Initial Segment Voicing</td>
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<tr>
<td>Initial Segment Voicing</td>
<td>Initial Segment Voicing</td>
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<td>FrequencyInitialDiphoneSyllable</td>
<td>Syllable Onset FB Consistency</td>
</tr>
<tr>
<td>FrequencyInitialDiphone</td>
<td>FrequencyInitialDiphone</td>
<td>Syllable Rhyme FF Consistency</td>
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<td>Root Consistency PC1</td>
<td>Syllable Rhyme FB Consistency</td>
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<td>Root Consistency PC2</td>
<td>Syllable Onset FB Consistency</td>
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<td>Root Consistency PC3</td>
<td>Syllable Onset FB Consistency</td>
</tr>
<tr>
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<td>Root Log Frequency</td>
<td>Syllable Rhyme FB Consistency</td>
</tr>
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<td>Root Written-Spoken Frequency Ratio</td>
<td>Root Written-Spoken Frequency Ratio</td>
<td>Syllable Onset FB Consistency</td>
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<td>Density</td>
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<td>Word Length in Letters</td>
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<td>Onset-Coda Phoneme Similarity</td>
<td>Vowel-Vowel Letter Similarity</td>
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<td></td>
<td>Number of Morphemes</td>
<td>Vowel-Vowel Similarity</td>
</tr>
<tr>
<td></td>
<td>Onset-Coda Phoneme Similarity x</td>
<td>Number of Morphemes</td>
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<tr>
<td></td>
<td>Number of Morphemes</td>
<td>Vowel-Vowel Similarity x Number of Morphemes</td>
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References


Cohen-Goldberg, A. M. (2012). Phonological competition within the word: Evidence from the phoneme similarity effect in spoken production. *Journal of Memory and Language*. [http://dx.doi.org/10.1016/j.jml.2012.03.007](http://dx.doi.org/10.1016/j.jml.2012.03.007)


