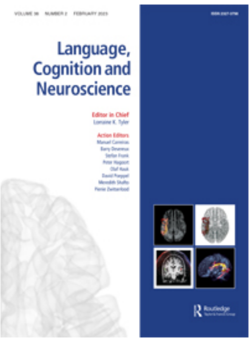

Language, Cognition and Neuroscience

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/plcp21

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LANGUAGE, COGNITION AND NEUROSCIENCE
https://doi.org/10.1080/23273798.2023.2189273

REGULAR ARTICLE

The activation of embedded (pseudo-)stems in auditory lexical processing: implications for models of spoken word recognition

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ABSTRACT
A large literature on visual word recognition has examined the role of (apparent) morphological structure by comparing suffixed (such as *treatment*), pseudo-suffixed (*pigment*), and non-suffixed (*dogma*) words with respect to their embeddings (*treat*, *pig*, *dog*). We examined the processing of these word types, as well as semantic controls, in an auditory primed lexical decision paradigm. The results show significant priming in all conditions relative to an unrelated baseline, with larger priming effects for truly suffixed words than for pseudo-suffixed and non-suffixed words. The results suggest that initial embeddings are activated in spoken word processing, and remain active in ways that do not depend on (apparent) morphological structure. We discuss the implications of these findings for models of lexical access that predict inhibition of disfavoured competitors and models that hold that attempted decomposition is driven by meaning relatedness between the carrier word and its possible embedded stem(s).

ARTICLE HISTORY
Received 7 December 2021
Accepted 22 February 2023

KEYWORDS
Morphological processing; embeddings; pseudo-suffixed words; spoken word recognition; stem priming

1. Introduction

A central question in the study of the mental lexicon is what role morphological structure plays in (pre)lexical processing. Theories on this topic range from those that hypothesise obligatory decomposition of words into constituent morphemes during processing, to those that deny the existence of any sort of word-internal structure whatsoever (for an overview, see Zwitserlood, 2018). A prominent literature on morphological processing contrasts three different types of words, which we refer to as *truly suffixed*, *pseudo-suffixed*, and *non-suffixed*. Truly suffixed words are usually described as morphologically complex, and have a meaning that is transparently related to that of the stem. An example is *treatment*, which consists of the stem *treat* and the affix -*ment*, and which has a meaning that is directly related to that of *treat*. Pseudo-suffixed words can also be broken down into an existing stem and an existing affix; however, there is no clear reason to believe that these words are morphologically complex. An example of a pseudo-suffixed word is *pigment*, which consists of the pseudo-stem *pig* and the pseudo-suffix -*ment*, but whose meaning is not related to the meaning of *pig*. Finally, non-suffixed words show a purely orthographic or phonological relationship of string overlap to a putative stem. An example is *cashew*, which contains the embedded word *cash*, but does not end in an existing affix in the language, unlike pseudo-suffixed words. For ease of reference, we will refer to the longer words in each of these three categories as *carrier words*; correspondingly, the (putative) stems will sometimes be referred to as *embeddings*.

These types of words and the relation to their embeddings have been studied extensively in prior work; the goal of this line of work is to determine whether there is automatic decomposition of words into possible morphemes. The reasoning is that if such decomposition occurs, pseudo-suffixed words should pattern with truly suffixed words in displaying facilitation of their embedded (pseudo-)stems in primed lexical decision experiments, because both types of words are decomposable into an existing stem and affix. Crucially, prior work that has examined this hypothesis has been done almost exclusively in the *visual* modality, such that the conclusions that are drawn concern morpho-*orthographic* decomposition (e.g. Rastle & Davis, 2008; Rastle et al., 2004, but see Beyersmann et al., 2019). With visually presented stimuli, both the beginning and the end of the carrier word are available to the processing system from the onset of presentation, and there is evidence suggesting that the letters that make up a word

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Supplemental data for this article can be accessed online at http://dx.doi.org/10.1080/23273798.2023.2189273.

are simultaneously read (e.g. Adelman et al., 2010; Bertram, 2011). For suffixed, pseudo-suffixed, and non-suffixed words, this means that the processing system has access to both the embedding and the carrier word at the same time.

Here we examine the processing of embeddings in the auditory modality. In contrast to the presentation of written words, speech unfolds incrementally. Therefore, it is not evident to the processing system from the beginning of presentation whether that word can be decomposed into (possible) morphemes or not. Studying the processing of embeddings in the auditory modality thus has the potential to shed new light on the question of how different types of words are processed. However, questions concerning the processing of embeddings in spoken words have not been systematically examined in the way that has been done in the visual modality, viz. in a stem priming experiment that compares suffixed, pseudo-suffixed, and non-suffixed words. The experiment reported here addresses this gap.

While the results connect in some ways with theories that are directed at visual processing, caution is required in making direct connections, given the many differences between reading words and hearing them. Part of what is at issue in the present paper is indeed whether (and how) such predictions should be transferred to auditory processing in the first place. More important for our purposes is that the findings have clear and direct implications for models of spoken word recognition, concerning the specific issue of whether embedded words are inhibited during lexical access. In addition, the work brings together different lines of research that have not always been in close contact. On the one hand, prior work on embeddings and morphological structure has almost exclusively been conducted in visual (or cross-modal) paradigms. On the other, embeddings have been examined to a limited extent in the auditory modality, but not with a systematic manipulation of morphological structure. Part of the contribution of the present paper is the demonstration of how (and why) these lines of work should be brought together.

1.1. Early visual processing

The comparison between suffixed, pseudo-suffixed, and non-suffixed words has surfaced predominantly in studies that examine the early stages of visual processing, asking how semantic relatedness (or the lack thereof) affects the pre-lexical stages of morphological decomposition. These studies typically make use of the masked priming paradigm, in which primes are only very briefly presented, with a stimulus onset asynchrony (SOA) of less than 60 ms, and are therefore unavailable for conscious report (Forster et al., 2003). Some report equivalent priming effects for pseudo-suffixed (*corner* → *CORN*) and truly suffixed (*cleaner* → *CLEAN*) prime-target pairs, but no priming effects for pairs that were only orthographically related (*brothel* → *BROTH*, in which *-el* is not an existing suffix in the language) (e.g. Beyersmann, Ziegler et al., 2016; Feldman et al., 2004; Longtin et al., 2003; Marslen-Wilson et al., 2008; McCormick et al., 2008; Rastle & Davis, 2003; Rastle et al., 2004; Zweig & Pylkkänen, 2009). These findings suggest that morpho-orthographic units of a complex word are analysed in early visual word recognition before semantic information plays a role (e.g. Meunier & Longtin, 2007; Rastle & Davis, 2008; Taft, 2004; Taft & Forster, 1975). Other studies have provided evidence against the idea that truly suffixed and pseudo-suffixed words produce the same effects, and argued instead that the early visual recognition of complex word forms involves the simultaneous access of morphological and semantic information, based primarily on increased facilitation with truly suffixed compared to pseudo-suffixed primes (e.g. Feldman et al., 2015; Feldman & O'Connor, 2009; Marelli et al., 2013; Marelli & Luzzatti, 2012; Milin et al., 2017; Schmidtke et al., 2017; Whiting et al., 2017).

Yet another group of studies employing masked priming paradigms has reported significant facilitation for embedded stems in suffixed, pseudo-suffixed, and non-suffixed words. Milin et al. (2017), for instance, showed that masked priming effects for pseudo-affixed primes (*limber* → *LIMB*) did not differ from pairs with form-overlap only (*limbo* → *LIMB*) (see also Andrews & Lo, 2013). Consistent with these results, Grainger and Beyersmann (2017) argued in favour of a non-morphological segmentation process that is initiated by edge-aligned embedded word activation. This holds not only for suffixed and pseudo-suffixed words, but also for non-suffixed words, such as *cashew* and its embedded word *cash* (see also Beyersmann, Cavalli et al., 2016). Under this view, embedded words are activated independently of whether they are accompanied by a suffix, a pseudo-suffix, or a non-suffix. In line with this approach, embedded stem activation has even been shown to occur in non-words (Taft et al., 2018). When a lack of (or smaller) facilitation effects are observed for non-suffixed words, this is argued to result from the activation of the whole-word representation (e.g. *cashew*), which generates inhibition on the embedded word representation (*cash*), thereby decreasing its activation level. In contrast, for suffixed and pseudo-suffixed words, the activation of the suffix boosts the activation of the edge-aligned embedded word representations.

1.2. Unmasked visual processing

In contrast to masked visual priming, auditorily presented primes are presented long enough to be consciously perceived by the participants. Therefore, *unmasked* visual studies that allow full and conscious processing of primes are more similar in this particular way to the processing of auditorily presented stimuli than masked paradigms. Unmasked visual studies that compared suffixed, pseudo-suffixed, and non-suffixed words are much less frequent than masked priming studies. In an early study, Drews and Zwitserlood (1995, Experiment 2) compared the contributions of morphological and orthographic similarity in an unmasked primed lexical decision experiment in Dutch (SOA: 300 ms). The results showed a strong facilitatory priming effect for morphologically related (i.e. truly suffixed) primes (*kersen* "cherries" →*kers* "cherry"), while primes that were only orthographically related to the target (*kerst* "Christmas" →*kers* "cherry") resulted in an inhibitory effect.

Rastle et al. (2000) further compared orthographic, morphological, and semantic effects by varying prime-exposure duration from situations in which the prime was masked to situations in which the prime was fully visible (with SOAs of 43 ms, 72 ms, and 230 ms). The different conditions consisted of truly suffixed words (*departure* → *DEPART*), pseudo-suffixed words (*apartment* → *APART*), non-suffixed words that were only orthographically related (*electrode* → *ELECT*), and semantically related words (*cello* → *VIOLIN*). The results showed that truly suffixed primes resulted in significant priming effects regardless of the SOA used, while pseudo-suffixed prime-target pairs showed priming only at the shortest SOA. The non-suffixed and semantic conditions resulted in significant effects only at the longest SOA: semantic priming had a facilitatory effect with the longer SOAs, and orthographic priming resulted in an inhibitory effect with the longest SOA. These studies suggest that non-suffixed and pseudo-suffixed words result in inhibitory effects in unmasked visual paradigms.

1.3. Auditory processing

The studies discussed above examined the processing of suffixed, pseudo-suffixed, and non-suffixed words in visual word recognition. In visual processing, the different (pseudo-)morphemes that make up a word are presented simultaneously, while spoken-word recognition occurs as the speech signal incrementally unfolds. It is possible that this crucial temporal difference between the visual and auditory modality has consequences for lexical access in general and for the activation of embeddings in particular. However, the auditory processing of different embedding types and their relationship to morphological structure has received relatively little attention.

One line of work to be considered comes from cross-modal priming paradigms, in which primes are presented auditorily and targets visually. Marslen-Wilson et al. (1994), for instance, ran a series of cross-modal priming experiments that manipulated the relatedness between primes and targets. The results showed that in cross-modal priming, recognition of a target stem was robustly facilitated when a morphologically complex prime was related to the target in a semantically transparent way (e.g. *punishment* → *punish*; Experiment 1 and 2). This condition corresponds to what we refer to as truly suffixed in the present paper. In contrast, pseudo-suffixed words (e.g. *casualty* → *casual*), in which no semantic relationship exists between the whole-word and the stem, did not result in significant facilitation of their pseudo-stem. Semantically related prime-target pairs (e.g. *idea* → *notion*) did show a significant priming effect, while non-suffixed pairs that were only related in form to the word-initial embedding (e.g. *bulletin* → *bullet*) did not produce reliable cross-modal priming (see also Longtin et al., 2003, Experiment 2). Gonnerman et al. (2007) further reported that the magnitude of morphological priming reflected the degree of semantic overlap between words in a series of cross-modal priming experiments. The largest priming effects were obtained when morphologically related prime-target pairs shared a high semantic relationship (e.g. *boldly* → *bold*); intermediate effects were obtained when they shared a moderate semantic relationship (e.g. *lately* → *late*); and only very small effects were obtained with pseudo-suffixed primes in which the pairs shared a low semantic relationship (e.g. *belly* → *bell*). These results suggest that at the level(s) of processing probed by a cross-modal priming task, semantic relationships are implicated in morphological decomposition.

An auditory study that examined the recognition of French suffixed, pseudo-suffixed, and non-suffixed words similar to those in the visual paradigms discussed above, but which did not use a priming paradigm, paired a lexical decision task with ERP (Beyersmann et al., 2019). The behavioural results from the lexical decision task showed that participants responded more slowly to non-suffixed words (e.g. *fortune* "fortune", containing the embedded word *fort* "strong" and the non-suffix ending *une*) than to truly suffixed (e.g. *pochette* "little pocket", consisting of the stem *poche* "pocket" and the diminutive suffix -*ette*) and pseudo-suffixed words (e.g. *mouette* "seagull", consisting of the pseudo-stem *mou* "soft" and the pseudo-suffix -*ette*), while no significant difference between the truly suffixed and pseudo-suffixed conditions was found. The ERP results further revealed enhanced N400 amplitudes for non-suffixed words compared to suffixed and pseudo-suffixed words, while, again, no difference between the truly and pseudo-suffixed conditions was found. These results suggest that in an auditory unprimed lexical decision task, suffixed and pseudo-suffixed words pattern together to the exclusion of non-suffixed words. However, another effect reported in this paper suggests a more complex picture: lexical decision latencies decreased with increasing whole-word frequencies, but increased with increasing embedded word frequencies, across all word types. This finding suggests that the embedding may be processed as a word also in the non-suffixed condition.

Although the processing of words similar to the type of suffixed, pseudo-suffixed, and non-suffixed words has not been systematically examined in unimodal auditory priming experiments, studies on related topics also provide relevant context. Auditory priming paradigms have, for instance, been used to examine the effects of *semantic opacity* on morphologically related words. An early study by Emmorey (1989) reported priming effects between auditorily presented morphological relatives that shared a morphological but no semantic relationship (e.g. *submit* → *permit*), but no priming between purely phonological relatives (e.g. *balloon* → *saloon*). In a similar vein, a unimodal auditory priming study by Creemers et al. (2020) reported robust priming effects for Dutch prefixed verb primes that were semantically transparent in relation to their embedded stem (*aanbieden* "offer" → *bieden* "offer") as well as for primes that were semantically opaque (*verbieden* "forbid" → *bieden* "offer") (see also Creemers & Embick, 2021). In addition, auditory priming paradigms have been used to examine potential processing differences between embeddings that are morphemes or not. Bacovcin et al. (2017) used rhyme priming to show that the recognition of a morphologically complex word as *snowed* was facilitated by the presentation of a word (*dough*) that rhymed with its embedded stem (*snow*), while a monomorphemic word like *code* was not. Wilder et al. (2019) further examined the differences between morphological and repetition priming (*frog/frogs* → *frog*). A pertinent comparison is that while morphological embeddings (*frogs* → *frog*) produced significant facilitation, phonological embeddings (*grape* → *grey*) did not. We discuss this in more detail below.

1.4. Lexical competition and inhibition

In the studies reviewed above, embeddings of different types are employed in contrast with morphologically complex words, with questions about morphological processing in focus. A different but related body of research in which embedding figures prominently grows out of research examining predictions regarding which forms are active and which are inhibited as lexical processing proceeds. Theories of spoken-word recognition typically assume that the incremental nature of auditory input has consequences for which words are active during lexical access (Marslen-Wilson, 1987; Marslen-Wilson & Welsh, 1978; McClelland & Elman, 1986; Norris, 1994). According to these models, multiple word candidates that are consistent with the incoming speech signal are simultaneously activated. Competition between simultaneously active words plays a central role, as it is necessary for the selection of the best candidate (see e.g. Cutler, 2012; Norris, 1994; Norris & McQueen, 2008; Weber & Scharenborg, 2012; Zwitserlood, 1989).

The Cohort model (Marslen-Wilson, 1987; Marslen-Wilson et al., 1994) assumes that the unfolding phonological input progressively narrows down the set of possible candidates (i.e. the cohort) until a winner is identified. The activation levels of different candidates are determined by the extent to which they (mis)match the acoustic-phonetic information in the input, such that the activation level of a cohort competitor is reduced when the unfolding speech input is no longer consistent with it. For example, in processing a word like *dogma*, the activation level of the competitor *dog* will be reduced as soon as it no longer matches the incoming speech signal, that is, when the /m/ in *dogma* is processed. In TRACE (McClelland & Elman, 1986) and Shortlist (Norris, 1994), simultaneously active candidate words compete directly with each other via lateral inhibition. These models assume that there are direct inhibitory connections between different words, and that all activated candidate words inhibit each other as a function of their bottom-up activation level. Activation levels are determined by a combination of the degree of similarity to the speech signal and the lateral inhibition received from other activated candidates. The candidate word that is most similar to the speech signal will receive the strongest activation and send out the strongest inhibition to the candidates with lower activation during competition. As a result, it is predicted that the subsequent processing of *dog* after *dogma* should display an inhibitory phonological priming effect. The Cohort model is of further relevance to the present study because of its assumption that morphological relatives do not compete for activation. This means that the word-initial cohort for *kind* includes *kin* and *kite*, but not *kindness*, *kindly*, or *kindhearted* (for discussion, see Balling & Baayen, 2008, 2012). For the type of words that form the focus of the current paper, this means that a truly suffixed word like *treatment* does not compete with *treat* in the same way as a pseudo-suffixed word like *pigment* competes with *pig* and a non-suffixed word like *dogma* competes with *dog*.

Prior experimental work has not conclusively established whether or not mismatching candidates are completely eliminated from the candidate set (e.g. Friedrich et al., 2013), or whether some residual activation of the disfavoured candidates is strong enough to be observed at the end of the speech input. Both phonological and semantic priming paradigms have employed embeddings to examine the issue of lexical competition, and some of these studies suggest that the impact of competing lexical entries can extend beyond the offset of a spoken word.

On the phonological side, several studies have examined priming effects in monosyllabic words that show overlap in onset position between primes and targets in spoken word recognition. As reviewed in Dufour (2008) (see also McQueen & Sereno, 2005), there is disagreement concerning the nature and locus of phonological priming effects, but several studies have reported that multiple-phoneme onset overlap between primes and targets (e.g. *sweet* → *sweep*) results in inhibitory effects (e.g. Dufour et al., 2007; Goldinger et al., 1992; Hamburger & Slowiaczek, 1996; Monsell & Hirsh, 1998; Slowiaczek & Hamburger, 1992). These studies reported that it takes longer to make a lexical decision to a target word when it is preceded by a prime word beginning with the same sound sequence (i.e. partial embeddings). For full embeddings (one word exhaustively contained in another), Wilder et al. (2019) reported that directionality matters in the activation of embeddings in monosyllabic carrier words. They obtained a phonological priming effect that was significantly different from the baseline condition for *gray* →*grape* ("superstring" targets), but not for *grape* → *gray* ("substring" targets). Wilder et al. (2019) interpreted this finding in line with the predictions of the Cohort model: in the processing of *grape*, *gray* is inhibited when the final segment /p/ is processed, as /p/ is inconsistent with *gray*.

For polysyllabic words, for which McQueen et al. (1995) estimated that 84% contain at least one embedded word in English, there exist only a few studies that have used phonological or identity priming paradigms. Friedrich et al. (2013), combining the recording of lexical decision responses and event-related potentials (ERPs) in a cross-modal auditory-visual word onset priming task in German, reported inhibition of lexical decision latencies for target words preceded by disyllabic onsets of cohort competitors (e.g. *ano* → *anorak*). In contrast, the ERP results showed a diverging pattern, suggesting that cohort competitors are not completely excluded from further processing. For word-final embeddings, Norris et al. (2006) showed that responses to *date* were slower after the prime *sedate* than after an unrelated prime. However, this inhibitory effect was not significant for primes in isolation, and was only robust when primes were presented in sentences.

Several studies that examined the activation of embeddings in polysyllabic words have used associative priming paradigms, rather than phonological or identity priming (e.g. Isel et al., 2003; Vroomen & De Gelder, 1997; Zhang & Samuel, 2015; Zwitserlood, 1989). Zhang and Samuel (2015), for instance, reported that embedded words (e.g. *ham*) are accessed at the semantic level when hearing the carrier word (*hamster*) in an auditory associative priming experiment, as *ham* in the prime *hamster* facilitated responses to the target *PIG*. Zhang and Samuel (2015) manipulated the type of embedding, including both initial (***ham**ster* → *PIG*) and final embeddings (*trom**bone*** → *DOG*). Their results showed significant priming of semantic associates only with initial embeddings, which are closest in kind to the non-suffixed condition used in the studies on morphological processing reviewed above. These results suggest that initial embeddings are still active after a spoken carrier word has been processed. Further evidence for the activation of embedded words comes from eye-tracking studies (e.g. Dahan & Gaskell, 2007; Salverda et al., 2003). Salverda et al. (2003), for instance, showed that when participants hear the word *hamster* they look more at a picture of *ham* than at an unrelated picture. However, these effects are believed to be short-lived due to inhibition of the activation of the embedding when the second syllable comes in.

In sum, the existing evidence from semantic and identity/phonological priming does not provide a conclusive answer to the question whether disfavoured cohort competitors are completely excluded after the carrier word is processed, or whether these candidates still exhibit activation that is strong enough to be measured in a priming paradigm. The types of words typically used in visual morphological priming paradigms, as discussed above, are clearly of direct relevance to models of spoken word recognition that predict that disfavoured competing word candidates, such as unintended embeddings, are inhibited when the speech signal is no longer consistent with it.

1.5. The current study

We present the results from an auditory primed lexical decision experiment that compared the processing of embeddings in spoken carrier words that are truly suffixed, such as *treat* in *treatment*, words that are pseudo-suffixed such as *pigment*, which consists of an existing stem *pig* and an existing affix *-ment* but is not actually morphologically complex, and non-suffixed words such as *cashew*, which consists of the existing stem *cash* but in which *ew* is not an existing affix in English. The experiment was designed to examine whether these words prime their embedded "stems" in the auditory modality. We further included semantically related prime-target pairs to examine the contribution of meaning relatedness to embedding effects.

Different theories of the mental lexicon, as discussed above, make contrasting predictions in terms of which of the three embedding conditions are expected to show facilitation in (pseudo-)stem priming. Theories that are specific to spoken-word recognition, such as TRACE (McClelland & Elman, 1986), Shortlist (Norris, 1994) and the Cohort model (Marslen-Wilson, 1984; Marslen-Wilson et al., 1994), assume competition between similar-sounding lexical candidates. These approaches therefore predict inhibition of phonological competitors, such as the embeddings in the pseudo- and non-suffixed conditions. Therefore, a lack of facilitation or even inhibition/interference of the embedded "stem" is predicted after the presentation pseudo-suffixed and non-suffixed primes. On the other hand, facilitation after suffixed primes is predicted, but only given the additional assumption that morphological relatives do not compete with each other.

Morphological processing theories that have mostly considered the visual modality also provide different perspectives. However, due to the difference in temporal properties between auditory and visual processing, and the difference between early, prelexical stages of processing and later stages of processing, it is not possible to attempt *direct* or "one-to-one" mappings between the current study and specific predictions derived from visual experiments employing similar materials. At the same time, it is possible to extract certain general expectations from that line of work, based on larger conclusions that have been drawn. If in auditory processing the semantics of the whole word (i.e. the carrier word) determines whether or not the word is decomposed, facilitation of the embedding after the presentation of suffixed words, but not after the presentation of pseudo-suffixed and non-suffixed ones would be expected (this is essentially the same prediction as the lexical competition theories). On the other hand, if all words which can be exhaustively parsed into an existing stem and suffix undergo automatic decomposition, suffixed and pseudo-suffixed words should produce stem priming effects, but non-suffixed words should not. Finally, if all initial embeddings are activated irrespective of whether or not the embedding is followed by an affix, facilitation in all three conditions would be predicted, since all three conditions contain an embedding.

2. Methods

2.1. Participants

Participants were 122 undergraduate students (79 female, mean age 19.55, sd 1.2, range 18–23) at the University of Pennsylvania, who received course credit as compensation for participation. Participants reported being native speakers of English. Ethical approval for the study was provided by the Institutional Review Board at the University of Pennsylvania, with protocol identification number #820591. Participants provided written informed consent prior to the start of the experiment.

2.2. Materials

Stimuli were prime–target pairs that were truly suffixed, pseudo-suffixed, non-suffixed, or semantically related. We included 20 prime-target pairs per condition, so that every participant saw 80 critical prime-target pairs of which half were unrelated. Sample critical items are given in Table 1; a full stimuli list can be found in the supplemental materials.

The pseudo-suffixed primes occurred with suffixes that exist in English and were therefore potentially recognisable, while the non-suffixed pairs did not terminate in a potential affix of English. Pseudo-suffixed prime-targets were selected such that the complex word and the stem did not share any meaning. In addition, based on Baayen et al. (2017), we excluded pseudo-suffixed pairs that shared some remote or archaic meaning, such as *butcher* → *butch* and *archer* → *arch* (see also Beyersmann, Ziegler et al., 2016). We further ensured that none of the stems in the pseudo-suffixed condition with the suffix *-er* were verbs, so that no additional transparent meaning of an agent noun ("someone who does something habitually or occupationally") could be formed.

Table 1. Conditions and sample critical items.

	Related prime	Unrelated prime	Target
Truly suffixed	treatment	basement	treat
Pseudo-suffixed	pigment	augment	pig
Non-suffixed	cashew	mildew	cash
Semantically related	painting	timing	art

The truly suffixed primes were selected such that the meaning of the prime was always related to the meaning of its stem. This was evidenced by high pairwise estimates of semantic similarity between primes and targets, based on latent semantic analysis (LSA; Laham, 1998, see Table 2).[1] The semantically related prime-target pairs were also selected based on their high pairwise LSA measures with their targets. A one-way ANOVA was performed on the LSA scores between primes and targets in the different conditions, which showed a significant difference ($F(7, 152) = 56.79$, $p < .001$). Post-hoc testing with Tukey's test showed that the LSA scores between related primes and targets in the truly suffixed condition differed significantly from those in the pseudo-suffixed ($p < .001$), and non-suffixed ($p < .001$) conditions, but not from the semantic condition ($p = .826$). The LSA scores between related primes and targets in the pseudo-suffixed and non-suffixed conditions also did not differ ($p = .623$).

The conditions were further controlled with different (pseudo-)suffixes appearing equally often in the pseudo-suffixed and truly suffixed conditions (following Feldman & O'Connor, 2009). In addition, due to the auditory presentation of stimuli, the targets were phonological sub-strings of their primes, which means that we excluded pairs like *legion* → *leg*. We also kept the orthography between primes and targets as similar as possible, excluding extremely dissimilar pairs like *aisle* → *eye*, but including pairs like *coral* → *core*.

All targets were high-frequency monosyllabic simplex words (mean duration 586 ms), see Table 2 for other target properties). Spoken word frequency measures were extracted from SubtLex-US (Lg10CD; Brysbaert & New, 2009), and the target frequency across conditions did not significantly differ ($F(3,76) = 1.356$, $p = .263$). Targets and primes were verbs, nouns, or adjectives. Prepositions, auxiliary verbs, and other (highly frequent) function words were excluded.

The primes were disyllabic words with main stress on the first syllable (mean duration 605 ms). For each related prime, a morphologically, semantically, and phonologically unrelated prime was selected, which was pair-wise matched with its related prime in word type (N, V, Adj) and frequency, as illustrated in Table 2. The unrelated primes, like the related primes, were disyllabic words with stress on the first syllable. The suffixes in the unrelated primes matched those of the corresponding related primes as much as possible. The unrelated primes in the non-suffixed and pseudo-suffixed conditions were mono-morphemic or pseudo-derived, in that they did not form morphological derivations of their stem. The unrelated primes had minimal phonological overlap and no semantic relatedness (i.e. low LSA scores; see Table 2) with the targets.

Table 2. Stimuli characteristics of related (Rel.) and unrelated (Unrel.) primes and targets in the different conditions.

	Mean frequency			Mean LSA to target	
	Rel. Prime	Unrel. Prime	Target	Rel. Prime	Unrel. Prime
Truly suffixed	2.29	2.29	3.08	0.53	0.06
Pseudo-suffixed	2.80	2.32	2.80	0.12	0.07
Non-suffixed	2.00	1.97	3.12	0.05	0.05
Semantically related	2.83	2.77	3.03	0.47	0.07

A set of 100 unrelated filler words were included to reduce the prime-target relatedness proportion. Of these filler words, half were monosyllabic and half were disyllabic. We also included 260 non-words, of which 130 were monosyllabic and 130 were disyllabic. Of the disyllabic words, 90 were generated by a script that calculated the frequency of onsets, vowels, and codas based on the CMU pronunciation dictionary (Weide, 1998) and SubtLex-US (Brysbaert & New, 2009). The script then randomly generated non-words so that more frequent onsets, vowels, and codas were more frequently selected. An example of such a non-word is */gɔ-wɪh/*. Moreover, 20 of the disyllabic non-words occurred with a real suffix but a nonce stem (e.g. */mʌ/-ness*), and 20 with a real stem but a nonce suffix (e.g. *snake-/βə/*). These stimuli ensured that participants could not determine the lexicality of the words and non-words based only on the first syllable.

In addition to the different types of carrier words, we also varied the intertrial interval (ITI) between primes and targets as a between-participants factor (including a short, medium, and long ITI). The ITI is the interval between the participant response to a stimulus n-1 and the onset of stimulus n.[2] In visual priming paradigms, manipulating the time interval between primes and targets (the Stimulus Onset Asynchrony or SOA) has been successfully used to track the time-course with which different types of information (e.g. semantic/phonological/morphological) become available during lexical access (see Marslen-Wilson et al., 2008; Rastle et al., 2000, for relevant examples). However, the manipulation of the ITI did not have an effect on the general pattern of priming effects in our auditory priming paradigm, hence, we pooled the results to provide better statistical power. An analysis that includes an interaction with ITI can be found in the supplemental materials.

2.3. Apparatus

The stimuli were recorded by an adult male speaker of American English in a sound attenuated booth, using a high-quality microphone. Sound files were segmented using Praat (Boersma & Weenink, 2015) and normalised to 70 dB SPL. The task was implemented in PsychoPy2 (Peirce, 2007). Stimuli were presented auditorily to the participants through Sennheiser HD 280 PRO headphones and response times were recorded using a button box.

2.4. Procedure

We used a continuous auditory lexical decision paradigm, in which primes and targets are not paired in any obvious way: participants perform a lexical decision task to each word or non-word that they hear. The use of this task is intended to minimise the role of strategic processing effects, and thus maximise effects resulting from automatic processing; see e.g. (McNamara & Altarriba, 1988; Shelton & Martin, 1992) , and Jones (2010) for discussion. A continuous priming paradigm with auditory presentation has been used to explore different types of relatedness between words (phonological, morphological, semantic) in a number of studies; see (Bacovcin et al., 2017; Creemers & Embick, 2021, 2022; Creemers et al., 2020; Monsell & Hirsh, 1998; Slowiaczek et al., 2000; Wilder et al., 2019)

Stimuli presentation was randomised throughout the experiment for each participant. As every target was paired with two primes (related/unrelated), we created two lists. Each participant was allocated to one of the two lists, so that they saw each target only once. As mentioned above, we manipulated the Inter-Trial Interval (ITI) as a between-participant factor, such that a third of the participants heard stimuli with a random Inter-Stimulus Interval of 200-400 ms, another third of 600-800 ms, and a final third of 1000–1200 ms. We refer the reader to the supplemental materials for more information on the ITI manipulation and an analysis of these results.

Participants were tested individually in a quiet room. They were instructed that they would hear existing and non-existing English words, and that they had to make a lexical decision to each word as fast and as accurately as possible. Participants could take two self-administered breaks during the experiment and the experiment lasted 22 min on average.

Table 3. Mean accuracy to targets by condition in Experiment 1 before further data trimming.

Condition	Unrelated	Related
Truly suffixed	96.9 (0.50)	99.3 (0.25)
Pseudo-suffixed	91.2 (0.82)	95.4 (0.60)
Non-suffixed	95.5 (0.59)	98.1 (0.39)
Semantically related	97.0 (0.49)	98.3 (0.37)

Note: Standard errors are given in parentheses.

3. Analysis and results

3.1. Analysis

The lexical decision latencies to targets were analysed as follows. Responses were coded for response type (word/non-word) and response time (RT; measured in ms from the onset of the sound file). One participant was excluded from further analysis because of overall low accuracy (69% accurate). Accuracy rates per condition are shown in Table 3.

Targets that were responded to incorrectly were discarded; targets whose primes received an incorrect response were discarded as well. As a result, there was a total exclusion of 856 observations (8.84% of all experimental items; 150 prime-target pairs in the truly suffixed condition, 291 in the pseudo-suffixed condition, 275 in the non-suffixed condition, and 140 in the semantically related condition). Based on RT-density plots, we considered RTs shorter than 250 ms and RTs longer than 5000 ms as extreme RTs. All pairs for which either the target or prime had an extreme RT (< 250 ms and > 3500 ms) were excluded, which resulted in the exclusion of 78 observations (0.88%).

The RT data were then log-transformed with a natural logarithm, and following minimal trimming procedures recommended by Baayen and Milin (2010), we removed outliers for individual participants for which Shapiro-Wilk tests for normality showed non-normal distributions. This resulted in the exclusion of 51 observations. In addition, we removed outliers for individual targets which showed non-normal distributions. We did this separately for the three different ITIs that were included to take into consideration the overall faster responses with a short ITI and the overall slower responses with a longer ITI. This resulted in the removal of 102 observations. In total, 153 observations (1.75%) were excluded through minimal by-participant and by-target data trimming.

We analysed effects on log-transformed target RT with linear mixed-effects models, using the lme4 package (Bates et al., 2015, version 1.1-28) in the R environment (R Core Team, 2016, version 4.1.2). Fixed effects were CONDITION (as a 4-level factor: truly suffixed, pseudo-suffixed, non-suffixed, semantically related) and PRIME TYPE (related, unrelated), and their interactions. CONDITION was treatment coded, with the reference level set to the pseudo-suffixed condition. PRIME TYPE was coded using sum contrasts with coefficients -0.5 for "related" and 0.5 for "unrelated". Post-hoc within-group comparisons were performed with emmeans (Lenth et al., 2018). We compared the levels of PRIME TYPE (unrelated/related) within each level of

CONDITION, with a Bonferroni adjustment for multiple comparisons.

We further included TRIAL NUMBER to control for effects of learning or fatigue, and log-transformed (natural log) PRIME RT and ITI (as a continuous variable) to control for the effect of the latency at the preceding prime and the time preceding the target on target recognition. To control for the properties of the stimuli, we further included TARGET FREQUENCY, and TARGET DURATION. The continuous variables were centred and scaled (i.e. z-scored). The random effects structure was selected through model comparison using likelihood ratio tests. All models considered here minimally include random intercepts for PARTICIPANT, PRIME, and TARGET. A model with the maximal random effects structure failed to converge, as did a model with random slopes for PRIME TYPE by both PARTICIPANT and TARGET. Adding a random slope of PRIME TYPE by TARGET alone did not produce a significant improvement over the intercepts-only model ($\chi^2 = 0.46$, $p = .80$). The random slope of PRIME TYPE by PARTICIPANT was a significant improvement over the intercepts-only model ($\chi^2 = 45.48$, $p <.001$), so this model was adopted. The model was refitted after excluding data points with absolute standardised residuals exceeding 2.5 standard deviations, which removed 223 data points (2.60%).

3.2. Results

The results and a visualisation are shown in Table 4 and Figure 1. A model summary table is provided in Table 5.

The analysis of the log-transformed RT data revealed a simple effect of PRIME TYPE (β =.053, p <.001) at the level of the pseudo-suffixed target type condition. The post hoc contrasts showed that all target type conditions showed significant differences between related and unrelated prime types: significant priming effects were found also in the truly suffixed (β = .097, p <.001), non-suffixed (β =.054, p <.001), and semantically related (β =.046, p <.001) conditions. These results indicate that it is not just after hearing a truly suffixed word like *treatment* that recognising the embedded stem *treat* is facilitated, but that hearing a pseudo-suffixed word like *pigment* facilitates recognition of *pig*, and hearing a non-suffixed word like *cashew* facilitates recognition of *cash*. The finding of a significant semantic priming effect further indicates that the paradigm used here is sensitive to semantic relatedness effects.

Table 4. Mean RTs to targets (in ms) after unrelated or related primes and priming effects in Experiment 1.

Condition	Unrelated	Related	Priming
Truly suffixed	1317 (5.13)	1190 (4.46)	126 (6.75)
Pseudo-suffixed	1328 (5.73)	1262 (5.36)	66 (7.84)
Non-suffixed	1340 (5.73)	1270 (5.16)	70 (7.71)
Semantically related	1324 (5.42)	1263 (4.94)	61 (7.34)

Note: Standard errors are given in parentheses.

The interaction between CONDITION and PRIME TYPE further revealed a difference between priming effects in the pseudo-suffixed and truly suffixed conditions (β =.044, p <.001), indicating a larger priming effect in the truly suffixed condition compared to the pseudo-suffixed condition. In contrast, no significant differences between the priming effects in the pseudo-suffixed and non-suffixed conditions (p =.964) and in the pseudo-suffixed and semantically related conditions (p =.508) were found. The lack of a difference between the pseudo-suffixed condition and the non-suffixed phonological condition is in line with results by Milin et al. (2017) in the visual modality, who also reported that pseudo-derived pairs did not differ from form-overlap-only pairs.

In addition, as expected for a lexical decision task, the model revealed a significant effect of TRIAL NUMBER (β = -.011, p <.001), showing that participants responded faster as the experiment progressed. TARGET DURATION was also significant (β =.034, p <.001), as expected as RTs were measured from the start of the sound file. A significant effect was also found for PRIME RT (β =.032, p < .001), indicating that participants responded slower to targets after having taken longer to respond to the prime. A further significant effect was found for ISI (β =.011, p =.003), showing that participants responded slower after a longer ISI. TARGET FREQUENCY (p =.061) did not turn out to be a significant predictor in the model.

Finally, we did an exploratory (post-hoc) analysis of the effects of whole-word and embedded word frequency on prime RTs on the same data as used above, along the lines of Beyersmann et al. (2019). For this analysis, we focussed only on the related primes in the suffixed, pseudo-suffixed, and non-suffixed conditions. Figure 2 shows prime RTs as a function of (embedded) word frequency per condition. The whole word frequency effects, in the left (A) panel of Figure 2, are similar to those reported by Beyersmann et al. (2019) for French carrier words. As expected, we see shorter RTs in response to higher-frequency words. A linear regression model (with condition coded with successive differences contrasts, comparing the differences between the means of the pseudo-suffixed vs. suffixed conditions and the non-suffixed vs. pseudo-suffixed conditions) revealed no significant interactions in the effect of whole-word frequency on prime RTs between the different conditions (pseudo-suffixed vs. suffixed: p = .32; non-suffixed vs. pseudo-suffixed: p =.33).

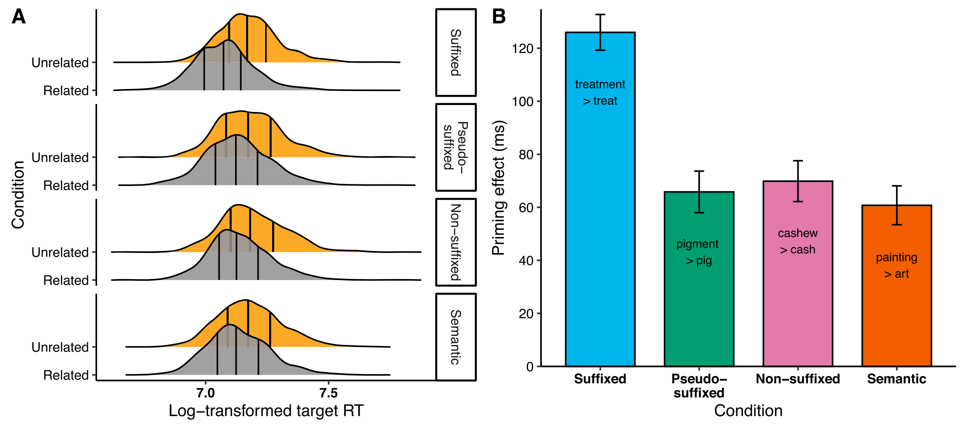

Figure 1. Response latencies to targets and priming effects. **A**: Stacked density plots for log-transformed (natural log) target RTs after unrelated/related primes in the different conditions. The lines correspond to the first, second, and third quartile. **B**: Priming effects in ms in the different conditions. Error bars represent ±1 standard error of the sampling distribution of differences.

Table 5. Fixed effects of the predictors in the linear mixed-effect model for response latencies (log-transformed RT).

Fixed effects	Estimate (β)	*t*-value	*p*-value
(Intercept)	7.172	660.308	**<.001**
Condition			
Pseudo-suffixed – Suffixed	−0.050	−3.466	**<.001**
Pseudo-suffixed – Non-suffixed	−0.017	−1.195	.236
Pseudo-suffixed – Semantic	−0.013	−0.932	.354
Prime type	0.053	6.450	**<.001**
Target Frequency	−0.009	−1.854	.068
Trial Number	−0.011	−10.028	**<.001**
ISI	0.011	3.049	**.003**
Target Duration	0.034	6.706	**<.001**
Prime RT (log)	0.032	25.656	**<.001**
Target type (Pseudo-suffixed – Suffixed) x Prime type	0.044	3.989	**<.001**
Target type (Pseudo-suffixed – Non-suffixed) x Prime type	−0.001	0.045	.964
Target type (Pseudo-suffixed – Semantic) x Prime type	−0.007	−0.665	.508

Notes: CONDITION was treatment coded with the reference level set to the Pseudo-suffixed condition; PRIME TYPE was sum-coded. Significant *p*-values (p <.05) are shown bold faced.

The results for embedded word frequency, in the right (B) panel of Figure 2, show that greater frequency of embeddings resulted in greater RTs for pseudo-suffixed words (perhaps due to greater competition). This is in line with the results reported in Beyersmann et al. (2019). In contrast to the results in Beyersmann et al. (2019), with truly suffixed words this is not the case: embedded word frequency in suffixed words appears to behave more like whole-word frequency in that frequency facilitates rather than hinders recognition. A linear regression model indeed revealed a significant interaction in the effect of embedded word frequency on prime RTs between the pseudo-suffixed and suffixed conditions (β =.09, p <.001), as well as between the non-suffixed and pseudo-suffixed conditions (β = -.04; p <.001). We note that this result should not be over-interpreted, as we did not design our experiment to examine the effects of frequency on prime recognition. However, the difference in slopes between suffixed and pseudo-suffixed words when it comes to embedded word frequency does suggest that embeddings in these types of words are processed differently, potentially indicating that morphological relatives (i.e. the embeddings in truly suffixed words) do not compete for competition in the same way as morphologically unrelated embeddings.

4. General discussion

The auditory priming experiment reported in this paper addressed the question of whether embeddings are activated in spoken suffixed, pseudo-suffixed, and non-suffixed words. We further included semantically related prime-target pairs to examine the contribution of meaning relatedness to embedding effects. The results of the present study provide several important contributions to the existing literature on embedded word priming effects, which we discuss in the next sections.

4.1. Activating onset-initial embeddings

The primary finding of this study is the robust and consistent priming effects in all conditions. The priming effects in the truly suffixed, pseudo-suffixed, and non-suffixed conditions suggest that word-initial embeddings are activated in spoken word processing, and that this happens irrespective of whether or not the carrier word contains an existing affix. This finding follows naturally from any approach that predicts that (initial) embeddings are activated after processing the carrier word, and irrespective of whether or not the embedding is followed by an (apparent) affix or not

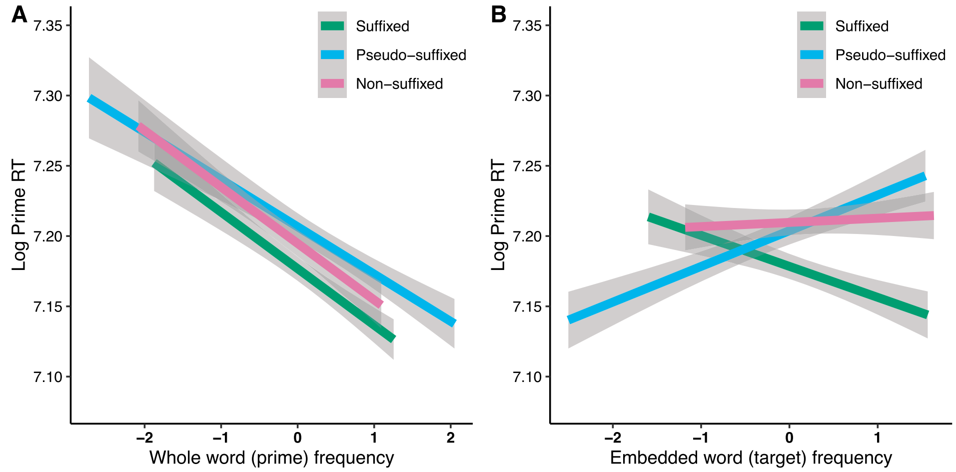

Figure 2. Log-transformed (natural log) reaction times (RT) to primes as a function of whole word frequency (left panel) and embedded word frequency (right panel) for suffixed words, pseudo-suffixed words, and non-suffixed words. Frequency measures are extracted from SubtLex-US (Brysbaert & New, 2009).

(e.g. Beyersmann, Cavalli et al., 2016; Grainger & Beyersmann, 2017). In addition, the significant priming in the semantic condition shows that the experiment also detects meaning-related effects. We focus the remainder of this section on the way our findings relate to earlier studies.

In earlier studies, pseudo-suffixed words (e.g. *corner* → *corn*) have reported mixed results. Visual *masked* priming studies have typically reported significant priming effects with pseudo-suffixed words (e.g. Beyersmann, Ziegler et al., 2016; Feldman et al., 2004; Longtin et al., 2003; Marslen-Wilson et al., 2008; McCormick et al., 2008; Rastle & Davis, 2003; Rastle et al., 2004; Zweig & Pylkkänen, 2009). However, these effects have been reported to disappear with longer SOAs (Rastle et al., 2000) in *unmasked* visual processing, and semantic relationships have been shown to form a precondition for stem activation in cross-modal priming as well (Gonnerman et al., 2007; Marslen-Wilson et al., 1994). The finding of a significant priming effect with pseudo-suffixed words in the current study, could, therefore, be considered surprising. However, the effect is in line with auditory lexical decision results reported by Beyersmann et al. (2019), who showed that pseudo-suffixed words patterned with suffixed words, and with several auditory priming experiments that showed significant priming effects in morphologically complex but semantically opaque words (Creemers et al., 2020; Emmorey, 1989).

While different results have been reported regarding pseudo-suffixed words, most visual (un)masked and cross-modal (with visually presented targets) priming studies have reported that target recognition was not facilitated by the prior presentation of a non-suffixed and only orthographically related prime (e.g. *cashew* → *cash*) (e.g. Beyersmann, Ziegler et al., 2016; Longtin et al., 2003; Rastle et al., 2004, but see Milin et al., 2017). The results in the current experiment showed a robust and significant priming effect in the non-suffixed condition. While this finding contrasts with earlier visual studies, it is in line with certain studies examining the activation of onset-initial embeddings in auditory processing, which showed that embeddings are not completely excluded from further processing (e.g. Zhang & Samuel, 2015). We discuss this in more detail below.

Having demonstrated that all three types of embedding are significantly primed by their carrier words, it must then be asked whether the way in which embeddings are processed *differs* among the three word types. Our results point to at least one such difference: the facilitation found in the truly suffixed condition is greater than that found in the pseudo-suffixed and non-suffixed conditions. This finding is compatible with a wide range of different theories. For instance, this difference is predicted by theories with morphological decomposition, in which a word like *treatment* is composed of the stem *treat* and the affix *-ment*, while *pigment* is not composed of two morphemes. It is compatible with other approaches as well, as the increased priming in the suffixed condition could also result from (some interaction of) shared form and meaning, as opposed to pseudo-suffixed and non-suffixed words where there is only shared form (see e.g. Gonnerman et al., 2007; Raveh, 2002). Generally speaking, the increased priming for suffixed words is compatible with any approach that predicts form- and meaning-overlapping words to show more priming than those showing formal overlap alone. The present experiment was not designed to distinguish between these theories but paves the way for such comparisons, in ways that are further discussed below.

4.2. Implications for models of spoken word recognition

The finding that the recognition of initial embeddings (e.g. *treat*, *pig*, *dog*) is facilitated after presentation of their carrier words not only in suffixed word conditions (e.g. *treatment*) but also in pseudo-suffixed (*pigment*) and non-suffixed (*dogma*) conditions suggests that these embeddings still have a higher-than-baseline (i.e. non-zero) level of activation after the carrier word has been processed. The residual activation of the disfavoured candidates is strong enough to be observed beyond the offset of a spoken word, which suggests that these candidates, which mismatch the speech signal, are not completely eliminated from the candidate set.[3]

These results are compatible with results from different tasks that used spoken stimuli, such as associative priming (e.g. Zhang & Samuel, 2015), combined lexical decision and ERP (Friedrich et al., 2013), and eye-tracking (e.g. Dahan & Gaskell, 2007; Salverda et al., 2003). Dahan and Gaskell (2007), for instance, showed that competition between candidate words may extend over a substantial period, even after the signal has provided strong bottom-up evidence in favour of a particular word. Using a visual world paradigm, they found that even when the speech signal contains sufficient information for ruling out a lexical competitor (e.g. *koffie* "coffee" to a target *koffer* "suitcase"), listeners still considered the competitor to a greater degree than they considered phonologically unrelated distractors. An important question is *why* the processing system still considers embeddings. Dahan and Gaskell (2007) argued in favour of a Bayesian account that assumes that listening is a process of decoding perceptual information passing through a noisy channel (because the stimulus itself is noisy, or because there is noise in the perceptual system), as proposed by Norris (2006) for visual word recognition. Due to the noisy channel, there is some probability that the word that most closely matches the input will not be the correct word. An ideal observer, hence, must also take the prior probabilities of the words into account, leading to a *gradual*, rather than instantaneous, process of reducing the activation of competitors.

In sum, the significant priming effects in the pseudo-suffixed and non-suffixed conditions in the current study suggest that disfavoured competing lexical items, such as embeddings, are not completely excluded from further processing, but instead exhibit residual activation that is strong enough to be measured in a priming paradigm. On this point, we note that findings for different language processing phenomena have been reported that further suggest that the processing system keeps track of disfavoured or less efficient word candidates. Gwilliams et al. (2018), for instance, showed that acoustic-phonetic information is not lost once a phonological categorisation is derived in the processing of ambiguous onset phonemes. Instead, acoustic-phonetic information is maintained and can be reanalysed in light of subsequent context, if it turns out that the wrong phoneme was initially chosen as the "winning" candidate. Gaston (2021) further provided evidence for the activation of lexical items that were incompatible with the preceding syntactic context. Moving forward, an intriguing possibility would be to connect these findings with ongoing discussion of how lexical processing is computed at the neural level. For example, the theoretical opposition examined in Gagnepain et al. (2012) explicitly contrasted inhibition-based approaches with those involving segment prediction, and presented evidence in favour of the latter. The convergence suggested by these findings– or at the very least, the focus on inhibition and its alternatives– points to important opportunities for future research.

4.3. Potential role for syllable structure

Our findings concerning embedded-word activation provide insight into the way in which competition is resolved during lexical access. However, the activation of embeddings may depend on a combination of effects, including the size of the embedding relative to the size of the carrier word, the position of the embedding (e.g. Zhang & Samuel, 2015), and possibly potential segmentation cues as well. Regarding this latter point, the fact that we employed disyllabic primes may have played an important role in producing the relevant facilitatory effects. The embeddings in our study formed separate syllables within the carrier words, and were hence always left-aligned with syllable and word boundaries. At least some of the embeddings (i.e. those for which no resyllabification occurs, see below) were also right-aligned with syllable boundaries. In addition, our carrier words were stress-initial, such that all embeddings received main stress. There is some evidence that such segmentation cues, which are relevant for word boundary detection, may influence the activation of embeddings (for discussion, see Norris et al., 2006). For instance, (the onsets of) strong syllables have been shown to play a special role in lexical access in English

(Cutler & Norris, 1988; Norris et al., 1997). Zwitserlood (2004) further reported that morphological effects depended on syllabic cues: for words in which syllabification leaves the morpheme intact (i.e. no resyllabification across morpheme boundaries), access to lexical entries containing that morpheme was shown to be more efficient and faster.

The use of polysyllabic versus monosyllabic carrier words may further explain some of the discrepancies between the current findings and some results of phonological/identity priming with embeddings as discussed in the Introduction. For instance, Wilder et al. (2019) showed a lack of facilitation when monosyllabic carrier words functioned as primes with a substring of the prime as the target (e.g. *grape* → *gray*). Our results (using a similar paradigm as Wilder et al., 2019) showed significant facilitation in the non-suffixed condition, which is equivalent to the substring target condition employed in Wilder et al. (2019). For the reasons outlined above, this difference may be caused by the fact that the (monosyllabic) stimuli used in Wilder et al. (2019) and the (disyllabic) stimuli in our non-suffixed condition differed in terms of the syllable structure of the primes.[4]

4.4. Further directions

In our introductory remarks, we discussed how prior behavioural studies of pseudo-suffixed words in the visual modality have been employed as part of an argument concerning morphological decomposition. By way of concluding this paper, we would like to focus attention on the ways in which our results pave the way for further examination of these questions in the auditory modality. In our view, the key further directions to explore should focus on potential processing differences between (i) suffixed and pseudo-suffixed words and (ii) pseudo-suffixed and non-suffixed words.

As for the first comparison, an important question is whether the embeddings in suffixed and pseudo-suffixed words are treated in the same way by the processing system. It could be asked, for example, whether the relative contributions of the embedding and the (pseudo-)affix to variables of interest differs in these conditions. If, for example, the effects of embedding frequency versus whole word frequency differed systematically for suffixed and pseudo-suffixed words, this provides evidence that they are processed differently. While the results in Beyersmann et al. (2019) for French suggest that this is not the case, our exploratory analysis of the effects of stem frequency on prime RTs showed a difference between suffixed and pseudo-suffixed words: with pseudo-suffixed words the RTs increased as the stem frequency increased, while RTs decreased with truly suffixed words. Although merely a suggestion at this point, this could indicate that morphological relatives (i.e. the embeddings in truly suffixed words) do not compete for competition in the same way as embeddings in words that are only pseudo-complex. On this point, recall the assumption from the Cohort model highlighted above that morphological relatives do not compete with one another. Also in Cohort-inspired terms, it could be asked whether the uniqueness points of both the stem and the (pseudo-)affix play the same role in predicting response times in both of these conditions or not (cf. Balling & Baayen, 2012).

Similar probes could be extended to the second comparison, between pseudo-suffixed and non-suffixed words. While there are no detectable differences between these conditions in the current study, this does not mean that these words are processed in the same way. In particular, processing differences could have been washed out by differences between the words that comprise these two conditions. It is therefore reasonable to ask (in an experiment that controls such factors) whether frequency or uniqueness point differences can be obtained between pseudo-suffixed and non-suffixed words. The key question here is whether the pseudo-affix is treated as a morpheme by the processing system even temporarily. If so, it would provide evidence in favour of decomposition analogous to the findings that animated the study of pseudo-suffixed words in the visual domain.

To obtain such comparisons, it would be important to control the embeddings systematically, so that the same embedding occurs in both the suffixed and pseudo-suffixed conditions and in pseudo-suffixed and non-suffixed conditions. Experiments along these lines can be found in the visual modality. Feldman et al. (2015), for instance, compared suffixed words like *sneaky* to pseudo-suffixed ones like *sneaker*, and Milin et al. (2017) compared pseudo-affixed words like *limber* to non-suffixed ones like *limbo*. For reasons discussed in this paper, we believe that it would be fruitful to obtain these types of comparisons for spoken word recognition as well.

Finally, we noted at the beginning of the paper that we based our stimuli on studies directed at the early stages of visual morphological processing, where the key question concerns the presence/timing of semantic relatedness effects. The current study provides a foundation for a distinct but related set of questions concerning lexical semantic retrieval. As we have seen, embeddings are activated in spoken-word processing, irrespective of whether or not an existing suffix comes later in the word. It is then the details of *how* this activation works that are further at issue, in particular whether the activation of the form of an embedding also entails the retrieval of the meaning of that embedding and whether the presence or absence of a (pseudo)affix affects this process. This is related to what Zhang and Samuel (2015) did for embeddings in a mix of what we referred to as pseudo-suffixed and non-suffixed words (see also Creemers & Embick, 2021), but future work could examine the influence of morphological structure on the activation or retrieval of embedded stems in more detail.

4.5. Concluding remarks

In sum, our findings provide evidence that initial embeddings are activated in auditory processing in a way that does not appear to rely on morphological structure. This basic finding concerning embeddings provides evidence against the idea that there is full inhibition of disfavoured competitors during processing, at least for the types of words studied here. We have further shown how the results presented here pave the way for finer-grained studies of spoken word processing, examining potential differences between the processing of words that appear to have morphological structure and those that do not. This brings into the auditory modality a set of questions about automatic decomposition that has been at the centre of an extensive debate in work employing the visual modality.

Notes

1. http://lsa.colorado.edu/.
2. In 69 instances in our data from 24 participants, the responses occurred prior to the end of the word being presented; these early responses did not result in the sound file being truncated. In these instances the ITI was measured from the end of that word. After data trimming (see below), only one of these instances remained.
3. Recall that we also included an ITI manipulation in the present experiment, the results of which can be found in the supplemental materials; similar priming effects are found even with a relatively long ITI of 1000–1200 ms, suggesting that the activation is still present after further time has elapsed.
4. A further question of interest concerns how cross-linguistic differences in syllable structure might manifest themselves in the activation of embeddings; for example, the French (pseudo-)affixes employed in Beyersmann et al. (2019) appear to be vowel initial, and thus induce resyllabification of the (pseudo-)stem; stress properties of French versus English would also be relevant here (see Zhang & Samuel, 2015, for discussion). Our experiment was not designed to probe this particular set of points, as the stimuli were mixed with respect to whether and how much resyllabification of the embedding is involved in primes. Syllabic effects could be manipulated in further work to determine their influence on how they affect the activation of embeddings, both within and across languages. For review and discussion of how syllabic effects might be manifested in the visual modality, see Petrosino (2020).

Acknowledgments

Many thanks are due to Robert J. Wilder and Amy Goodwin Davies for invaluable help and feedback. Thanks are also due to Akiva Bacovcin, Kobey Shwayder, Roberto Petrosino, the members of the Embick lab and the Language Variation and Cognition Lab at Penn, and the audiences at the 11th International Conference on the Mental Lexicon and the 10th International Conference of Experimental Linguistics.

Data availability statement

The data that support the findings of this study are openly available on the OSF: https://osf.io/whgfy/.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Institutes of Health [grant number R01HD073258].

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