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Processing Lexically Embedded Spoken Words

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A large number of multisyllabic words contain syllables that are themselves words. Previous research using cross-modal priming and word-spotting tasks suggests that embedded words may be activated when the carrier word is heard. To determine the effects of an embedded word on processing of the larger word, processing times for matched pairs of bisyllabic words were examined to contrast the effects of the presence or absence of embedded words in both 1st- and 2nd-syllable positions. Results from auditory lexical decision and single-word shadowing demonstrate that the presence of an embedded word in the 1st-syllable position speeds processing times for the carrier word. The presence of an embedded word in the 2nd syllable has no demonstrable effect.

A primary goal of theories of spoken word perception is to account for the ease with which listeners segment the continuously varying speech stream into words (Cole & Jakimik, 1980; Norris, 1994). It is well known (see Luce & Pisoni, 1987) that the speech signal contains no consistent acoustic markers that reliably indicate the beginnings and ends of words in fluent speech. However, despite the lack of physical cues to word boundaries, the listener is remarkably successful at parsing the speech stream into discrete lexical items.

Various solutions to the problem of lexical segmentation have been proposed. One of the simplest has been to assume that the listener knows where one word begins by identifying where the previous word ended (Cole & Jakimik, 1980). Although such a strategy may have some utility, it will undoubtedly meet with limited success, primarily because of the problem of *lexical embeddedness,* which refers to the presence of shorter words embedded within longer words. For example, the word *cherish* contains the embedded word *chair.* The simple strategy of positing word boundaries at the ends of all possible lexical items would lead to an incorrect parse of *cherish,* leaving a stranded syllable (i.e., *ish*) that is consistent with no independent lexical entry in memory. Thus, the successful listener must adopt a solution to segmentation that is not so brittle as to fail in the face of embedded lexical items.

Lexical embeddedness in English is widespread. Using a 20,000-word on-line lexicon, Luce (1986) found that 62% of words weighted for frequency were embedded in the beginnings of longer words (e.g., *car* in *carpet;* see also Frauenfelder & Peeters, 1990, for a similar analysis of Dutch). McQueen and Cutler (1992), in an analysis of approximately 25,000 transcriptions of British English, found that 94% of polysyllabic words begin with monosyllabic words. Using the gating task, Grosjean (1985) and Bard, Shillcock, and Altmann (1988) demonstrated the implications of this kind of lexical embedding for segmentation of spoken words from connected discourse: Many times, decisions about the identities of words must be deferred until later acoustic–phonetic information has accrued in order to resolve ambiguities regarding the placement of word boundaries.

To further assess the prevalence of lexical embeddedness, we examined the on-line lexicon used by Luce (1986). The percentages of multisyllabic words (having two through seven syllables) that contain embedded words are shown in Figure 1. (Only those embedded words coincident with entire syllables of the carrier words were counted.) As shown in Figure 1, the presence of embedded lexical items in longer carrier words is quite common. Indeed, almost 60% of bisyllabic words—the most frequent of the multisyllabic words examined—contain embedded lexical items.

The phenomenon of lexical embeddedness raises a number of questions that have implications not only for segmentation but also for more general theoretical issues regarding the perception of spoken words, both in isolation and in connected discourse: Does the listener (at least implicitly) entertain all possible hypotheses regarding embedded and carrier words during the recognition process? That is, does the stimulus word *cherish* activate representations for *chair* and *cherish,* or is a single interpretation favored, for example, the one that corresponds to the longest word possible? If lexical embeddedness has demonstrable effects on processing, do embedded items facilitate or interfere with recognition of the longer words in which they occur? And do items embedded in the beginnings of words behave the same as items embedded at the ends of words? Questions regarding the role of lexical embeddedness in spoken word recognition may have important implications for theoretical accounts of the nature of lexical activation and processing (see Norris, 1994).

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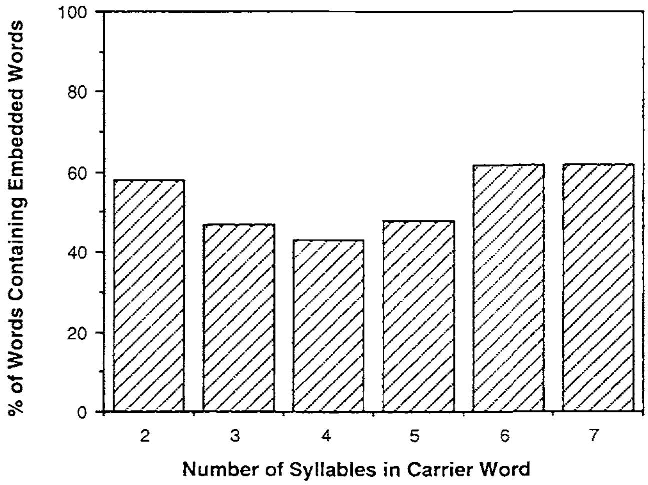

Figure 1. Percentages of multisyllabic words in a 20,000-word lexicon that contain one or more embedded words.

Current attempts to explain spoken word recognition make various predictions about the role of lexical embeddedness in processing. Some of these approaches make identical claims, although not necessarily for the same reasons. Other approaches, however, make contrasting predictions regarding the potential effects of lexical embeddedness.

In the cohort theory of spoken word recognition (Marslen-Wilson & Welsh, 1978), a set of candidates (i.e., the "cohort") is activated in memory on the basis of information in the onsets of spoken words. After activation of the cohort, the candidate set is winnowed until a unique item remains that is consistent with the available sensory and contextual information. In the early version of cohort theory, embedded words entered into the cohort only if they coincided with the beginnings of the carrier words (e.g., *chair* in *cherish*). An embedded word occurring later in the carrier word (such as *stress* in *distress*) would not be activated, because the embedded item occurring later would not be a member of the cohort. In later versions of the theory (Marslen-Wilson, 1987, 1993), this constraint was relaxed. Nonetheless, despite the fact the early cohort theory claimed that an initial embedded item would be activated along with the carrier word in which it occurs, neither present nor previous versions of the theory actually predict that embedded items should affect processing. If lexical uniqueness points are held constant, processing should neither be slower nor faster for words containing initial embedded items.

Swinney (1981) has offered a somewhat different proposal that nonetheless makes predictions similar to those of the earlier version of the cohort theory. According to Swinney's "minimal accretion principle," when faced with lexically embedded items, listeners opt for the interpretation that spans the longest word. For example, in processing a potential two-word item such as *kidney,* the carrier word would be the preferred interpretation and not the two-word utterance, *kid knee.* Again, it is unclear whether the mere presence of embedded words should have consequences for processing. However, the principle clearly states that embedded items occurring later should not result in ambiguous parsings of the speech stream if a single interpretation consistent with the longer carrier word is viable. In short, both Swinney's minimal accretion principle and Marslen-Wilson's (1987, 1993; Marslen-Wilson & Welsh, 1978) cohort theory predict little effect of later occurring embedded words on processing. Although both accounts hypothesize independent activation of initially embedded items, they are silent as to the precise effects these items may have on processing of the carrier word.

Proposals regarding lexical embeddedness contrary to those of Marslen-Wilson (1987, 1993; Marslen-Wilson & Welsh, 1978) and Swinney (1981) come in many forms. For example, Cutler (1989) discussed a possible model of lexical access in which form-based lexical representations may be activated at the onset of each syllable. Thus, every syllable that corresponds to a word will result in activation of a lexical item in memory. Cutler and Norris (1988) modified this more radical activation hypothesis by invoking the "metrical segmentation strategy," in which lexical hypotheses are generated on the basis of *strong* syllables. (Strong syllables, not to be confused with *stressed* syllables, are those containing full vowels.) Regardless of where they occur in the carrier word, embedded items coinciding with strong syllables should activate lexical representations (see also Charles-Luce, Luce, & Cluff, 1990; Cluff & Luce, 1990; Vroomen & de Gelder, 1997).

McClelland and Elman's (1986) TRACE model has much in common with the radical activation view; it also makes predictions that are remarkably similar to those of Swinney (1981; see also Frauenfelder & Peeters, 1990). According to TRACE, all lexical representations that are consistent with a given portion of the speech signal may be activated at any point. Thus, lexically embedded items at both the beginnings and endings of words may be activated. However, because of its architecture, TRACE clearly prefers interpretations corresponding to longer words. In a series of simulations, Frauenfelder and Peeters examined TRACE's processing of lexically embedded carrier words. Their simulations confirmed that within TRACE, embedded words may indeed be activated at any time. However, lateral inhibition among lexical nodes provides activation advantages to longer carrier words over later occurring embedded words. For example, the embedded word *seed* in the carrier word *precede* is inhibited by the previously activated carrier word and subsequently exerts little influence on the recognition process. In the case of initially embedded items, however, Frauenfelder and Peeters demonstrated that TRACE predicts strong activation for both the carrier and the embedded words. Of particular interest was their demonstration that TRACE predicts lower activation levels for carrier words containing embedded initial items than for words without competing embedded items. Because of lateral inhibition among multiply activated items (which include the carrier and embedded words), TRACE predicts that carrier words with initially embedded items should be processed more slowly than should longer words with no embedding. Norris's (1994) SHORTLIST, another connectionist model of spoken word recognition, makes similar predictions regarding the activation and processing of embedded words while providing a more plausible architecture for lexical processing.

To date, the empirical work on the effects of embedded words has failed to provide unequivocal support for any of these competing theoretical accounts. Using the cross-modal priming technique, Prather and Swinney (1977) found evidence for activation of embedded words occurring in the first, but not in the second, syllables of bisyllabic words. For example, auditory presentation of *boycott* primed a visual target related to *boy* but not one related to *cot,* a result that motivated the formulation of the minimal accretion principle. Pitt (1994) also failed to obtain evidence for the activation of second-syllable embedded words in bisyllabic carrier words, although he obtained evidence of activation of words embedded as the second syllable of nonword carrier items. For example, although the nonword *trolite* primed *dark, polite* failed to do so. Pitt proposed that the carrier word inhibits activation of noninitial embedded words.

Shillcock (1990), however, obtained a different pattern of results. For items in which the first syllables were not prefixes (e.g., *guitar*), he found evidence for activation of second-syllable embedded words (e.g., *tar*), suggesting that even noninitial embedded words may sometimes be activated.

Using the cross-modal priming technique, Luce and Cluff (1998) examined activation of component items in spoken bisyllabic words such as *hemlock,* which consist of two syllables that are words themselves. They obtained priming of related visual targets by second-syllable embedded items. For example, *hemlock* primed *key* as much as *lock* itself primed *key,* suggesting that *lock* is activated when *hemlock* is heard. Vroomen and de Gelder (1997), using the cross-modal priming paradigm, have also demonstrated activation of word-final embedded items.

The results from the cross-modal priming paradigm are obviously mixed. Overall, however, the bulk of the evidence suggests that embedded words are activated during recognition, although the precise conditions under which the effects of activation are evident have yet to be specified.

The effects of lexical embeddedness on the processing of spoken words have also been examined using the word-spotting task. In this task, participants attempt to detect an embedded word in a longer stimulus item as quickly as possible. McQueen, Norris, and Cutler (1994) found that second-syllable embedded words were harder to detect when the nonword carrier item constituted the beginning of a real word. For example, participants had more difficulty detecting *mess* in *demess* (which is the beginning of the word *domestic*) than *mess* in *nemess* (which does not begin a real word in English; see also Norris, McQueen, & Cutler, 1995). These results demonstrate that carrier items in which lexically embedded words occur compete with the embedded items for recognition. (See Norris et al., 1995, for a discussion of the role of metrical information in competition effects among embedded items.)

Research using the cross-modal priming and the word-spotting tasks has thus examined activation and detection of lexically embedded words. However, in neither of these tasks are participants required to respond to the carrier word itself. These tasks therefore provide no direct information about how the presence of an embedded word affects processing of the larger word.

The research that has directly examined the processing of carrier words containing embedded items has been conducted exclusively in the visual modality. Taft and Forster (1976) presented participants with bisyllabic stimuli in which one or both syllables were words. However, the bisyllabic stimulus itself was always a nonword. In a lexical decision task, participants were slower to make a nonword response when the initial syllable was a word. The lexicality of the second syllable had no effect on response times. In a second experiment, Taft and Forster presented participants with bisyllabic words, half of which contained first syllables that were themselves high-frequency words. The other half contained initial syllables that were either low-frequency words or nonwords. Word responses were faster to the stimuli that began with high-frequency embedded words.

These findings based on printed words demonstrate that when the first syllable of a bisyllabic carrier item is a word, recognition of the carrier item itself is affected, regardless of the lexicality of the carrier word. Moreover, in Taft and Forster's (1976) experiments with real word carriers, the presence of an embedded word facilitated recognition of the carrier word, a result that contrasts with the findings from the word-spotting task, in which only interference effects between carrier and embedded words were obtained. At present it is unclear whether the source of these differential effects lies in the task, in the modality of processing, or in both.

We were interested in examining the effects of lexical embeddedness on recognition of *spoken* words using tasks that, unlike cross-modal priming and word spotting, directly measure processing of the carrier word. Using both auditory lexical decision and single-word shadowing tasks, we examined processing times for carrier words with and without lexical embedding. We tested two hypotheses about the possible consequences of embedded words on recognition of the carrier word: First, we attempted to determine if an embedded word slows or interferes with processing of a carrier word because of competition between the embedded and carrier words, as predicted by models such as TRACE and SHORTLIST. Alternatively, we attempted to determine if the presence of an embedded word may actually facilitate recognition of the carrier word. Although facilitation between embedded and carrier words is not predicted by any current model of spoken word recognition, models in which segmental and lexical levels have bidirectional, interlevel feedback have possible mechanisms for producing facilitatory effects. In particular, excitatory feedback loops between segment and word nodes may produce heightened activation of carrier words with embedded items compared with matched, unembedded words. (This result would only arise, of course, in the absence of compensating or overwhelming intralexical inhibition.) We furthermore attempted to determine if effects of lexical embeddedness vary as a function of the position of the embedded item within the carrier word. As previously discussed, the radical activation hypothesis predicts effects of embeddedness regardless of the position of the embedded item. Other theories, for various reasons, suggest that embedded items should only exert their influence if embedded at the beginnings of carrier words.

In short, we examined processing times for carrier words that did or did not contain embedded lexical items. Furthermore, we examined recognition performance in two experimental tasks—single-word shadowing and auditory lexical decision—to ensure that any obtained effects were not the result of peculiarities of a particular experimental methodology. We examined the effects of lexically embedded items occurring at the beginnings of words in Experiment 1. In Experiment 2, we examined stimuli in which embedded lexical items occurred later in the carrier words.

Table 1
Stimulus Statistics for Experiments 1 and 2

	Experiment 1		Experiment 2	
Variable	Word initial	Nonword initial	Word final	Nonword final
Total duration (ms)	692	679	795	799
First-syllable duration (ms)	367	352		
Log frequency	.90	.89	.55	.46
Subjective familiarity	6.8	6.6	6.6	6.7
Lexical uniqueness point (in phonemes)	3.6	3.8	4.2	4.3
Log frequency-weighted initial cohort size	3.0	2.9	3.0	2.9

Experiment 1

Method

Participants

Forty-four members of the State University of New York at Buffalo community participated in the experiment. Participants either received credit for an introductory psychology class or were paid $4 for their participation. All participants were right-handed, native English speakers and reported no history of speech or hearing disorders.

Materials

The stimuli consisted of 18 pairs of bisyllabic words. In one member of each pair, the first syllable constituted a word (e.g., *cherish*). These are referred to as the *word-initial* stimuli. The first syllable of the other member of the pair was a nonword (e.g., *flourish*). These are referred to as the *nonword-initial* stimuli. Final syllables for all stimuli were nonwords. All stimuli were produced with primary stress on the first syllable. The complete list of stimuli is shown in Appendix A.

An embedded lexical item was defined as an entire syllable corresponding to a real word. Likewise, a syllable was defined as a nonword if the whole syllable failed to map onto an existing lexical item. Given Vroomen and de Gelder's (1997) demonstration that an embedded item must span an entire syllable before evidence of lexical activation is observed, we felt justified in adopting the whole-syllable criterion for determining lexicality. In addition, in determining lexicality for embedded syllables, we treated ambisyllabic segments as belonging both to initial and final syllables.

To ensure that the participants were familiar with the target words, we chose only words with subjective familiarity ratings of 4 or above on a 7-point scale, ranging from 1 (*don't know the word or its meaning*) to 7 (*know the word and its meaning;* see Nusbaum, Pisoni, & Davis, 1984).

The word- and nonword-initial stimuli were matched on overall duration, duration of the first syllable, log frequency (based on Kučera & Francis, 1967), lexical uniqueness point, and frequency-weighted initial cohort size: for cohort size, $F(1, 34) = 1.12$, $p = .30$; for subjective familiarity, $F(1, 34) = 1.14$, $p = .29$ (all other $Fs < 1$). Mean values for these variables are shown in Table 1. Transitional probabilities from first to second syllables were also matched. All lexical statistics were computed by means of a 20,000-word lexicon with computer-readable phonetic transcriptions.

In addition to hearing the target stimuli, participants heard an equal number of one-syllable words. Participants in the lexical decision task also received an equal number of one- and two-syllable nonwords. All of the nonwords were phonotactically permissible in English. Half of the two-syllable nonwords diverged from their word cohort in the first syllable, and half in the second syllable. Nearly half of the two-syllable nonwords contained words as their first syllable.

All stimuli were recorded by a female speaker (Emily A. Lyons) in a sound-attenuated room. Both words and nonwords were spoken in list format. The stimuli were low-pass filtered at 4.8 kHz and digitized at a sampling rate of 10 kHz by means of a 12-bit analog-to-digital converter. The words were edited with a waveform editor and placed into individual files.

Procedure

The two stimulus conditions—word initial and nonword initial—were presented in two task conditions: auditory lexical decision and single-word shadowing. No participant took part in more than one condition.

Lexical decision. In this task, participants indicated whether an auditorily presented stimulus was a word or a nonword by pressing an appropriately labeled button on a response box as quickly as possible. "Word" responses were made with the right hand by pressing a button on the right that was labeled *word;* "nonword" responses were made with the left hand by pressing a button on the left labeled *nonword.* Responses were measured from the onset of the stimulus to the button-press response. Stimuli were presented over headphones at a comfortable listening level.

A minicomputer controlled stimulus presentation and response collection. Participants were instructed to respond as quickly and as accurately as possible. Prior to the experimental trials, participants were given a block of 10 practice trials to familiarize them with the task.

Shadowing. In this task, participants were presented, by means of headphones, with spoken words, which they repeated into a microphone. Participants were tested individually in a booth equipped with a voice key interfaced to the computer, which again controlled stimulus presentation and response collection. Participants were instructed to repeat the word they heard as quickly and as accurately as possible into a microphone attached to the headphones. The voice key was triggered by the onset of the shadowing response. Response times were measured from the onset of the stimulus to the onset of the shadowing response. Accuracy was monitored by the experimenter.

The stimuli differed from the lexical decision task in that only word items were used. Before the experimental trials, participants were given a block of 10 practice trials to familiarize them with the task.

Results

Separate two-way analyses of variance (ANOVAs; First Syllable Lexicality × Task) were performed on response latencies and percentages correct for the target-word responses. First-syllable lexicality was a within-subjects variable, and task was a between-subjects variable. Analyses were performed both by participants (indicated by the subscript *s*) and by items (indicated by the subscript *i*). Only correct responses were analyzed. Latencies and accuracy scores for lexical decision and shadowing are shown in Table 2.

Latencies

Significant effects of task, $F_s(1, 42) = 14.18, p < .0005$, $F_i(1, 68) = 36.32, p < .0001$, and first-syllable lexicality, $F_s(1, 42) = 28.47, p < .0001$, $F_i(1, 68) = 4.88, p < .04$, were obtained. The interaction of the two variables was not significant (both $Fs < 1$). Reaction times (RTs) in the shadowing task were 126 ms faster than RTs in the lexical decision task. Word-initial stimuli were responded to 46 ms more quickly than were nonword-initial stimuli.[1]

Accuracy

A significant effect of task, $F_s(1, 42) = 46.58, p < .0001$, $F_i(1, 68) = 315.12, p < .0002$, was obtained for accuracy. Accuracy was 11% lower in the lexical decision task than in the shadowing task. The effect of first-syllable lexicality was significant by participants, $F_s(1, 42) = 14.87, p < .0004$, but not by items, $F_i(1, 68) = 3.06, p > .05$. The interaction of the two variables was not significant by items or participants: $F_s(1, 42) = 3.71, p > .05$ ($F_i < 1$).

Discussion

The results of this experiment demonstrate that lexical embeddedness has demonstrable effects on processing: Carrier words with word-initial syllables were responded to more quickly both in lexical decision and in shadowing tasks than were carrier words with nonword-initial syllables. These results are not consistent with the predictions of the TRACE model, in which embedded items slow processing of the carrier word through lateral inhibition (see Frauenfelder & Peeters, 1990). We next report the results of a second experiment in which we examined the effects of lexical embedding at the ends of carrier words.

Table 2
Mean Response Latencies (in Milliseconds) and Percentages Correct for Experiment 1

	Stimuli							
	Word initial				Nonword initial			
Task	RT	*SE*	% correct	*SE*	RT	*SE*	% correct	*SE*
Lexical decision	939	17	91	1.0	991	22	84	2.0
Shadowing	819	27	99	0.6	858	30	97	0.9
Both	879	18	95	0.9	925	21	91	1.5

Note. RT = reaction time.

Experiment 2

Method

Participants

Forty-two members of the State University of New York at Buffalo community participated in this experiment. Participants either received credit for an introductory psychology class or were paid $4 for their participation. All participants were right-handed, native English speakers and reported no history of speech or hearing disorders. None of the participants in this experiment participated in Experiment 1.

Materials

The stimuli consisted of 26 pairs of bisyllabic words. In one member of each pair, the last syllable constituted a word (e.g., *chloride*). These are referred to as the *word-final* stimuli. The final syllable of the other member of the pair was a nonword (e.g., *chlorine*). These are referred to as the *nonword-final* stimuli. The initial syllables for all stimuli except two pairs were nonwords. The members of the pair, *paring–parish,* were initially intended to begin with the syllable /pæɹ/, which does not match the real word, /pɛɹ/. The distinction was later judged to be too subtle; we could not realistically expect the initial syllables not to be perceived as /pɛɹ/. Also, the pair *limbo–limber* was erroneously identified as having nonword-initial syllables. Nonetheless, the fact that these pairs contained initial-word syllables did not compromise the stimulus set. The lexicality of the initial syllables was not a focus of the present experiment, and because the lexicality of the initial syllables was the same for both members of the pairs, the individual members served as their own controls. Nineteen stimuli were

[1] The fact that the same pattern of findings was obtained for both the lexical decision and the shadowing tasks strongly suggests that the obtained effects are not an artifact of the idiosyncrasies of a particular task. However, in the shadowing task, there is the possibility that RT differences might be due to differences in the speed with which various initial phonemes trigger the voice key rather than to differences in the speed of processing the stimulus. Previous research (Gaygen & Luce, 1998; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997) has demonstrated that shadowing latencies reflect recognition times and not variables related to articulation or differential sensitivity of the voice key. Nonetheless, to examine directly these potential confounding variables, we conducted an additional experiment in which participants were told to delay their shadowing response until they were prompted to respond, which occurred 750 ms after the offset of the stimulus. We expected that if the effect of lexical embeddedness is due to processing differences, then delaying the response should eliminate the effect. However, if the responses are due to the speed with which various initial phonemes trigger the voice key, the effect should remain when the response is delayed. In fact, delaying the response did eliminate the RT difference.

produced with primary stress on the second syllable, and 7 with primary stress on the first. The complete list of stimuli is shown in Appendix B.

Again, only words with subjective familiarity ratings of 4 or above on a 7-point scale were chosen. The word- and nonword-final stimuli were matched on overall duration, log frequency, lexical uniqueness point, and frequency-weighted initial cohort size (all $Fs < 1$).[2] Mean values for these variables are shown in Table 1. Transitional probabilities from the first to the second syllables were also matched.

In addition to the target stimuli, participants heard an equal number of one-syllable words. Participants in the lexical decision task also received an equal number of one- and two-syllable nonwords. Again, all of the nonwords were phonotactically permissible in English; half of the two-syllable nonwords diverged from their word cohort in the first syllable, and half in the second syllable. Finally, as in Experiment 1, nearly half of the two-syllable nonwords contained words as their first syllable.

All stimuli were recorded by a female speaker (Emily A. Lyons) in a sound-attenuated room. Both words and nonwords were spoken in list format. The stimuli were low-pass filtered at 4.8 kHz and digitized at a sampling rate of 10 kHz by means of 12-bit analog-to-digital converter. The words were edited with a waveform editor and placed into individual files.

Procedure

The procedure was identical to that of Experiment 1.

Results

Separate two-way ANOVAs (Final Syllable Lexicality × Task) were performed on response latencies and percentages correct for the target-word responses. Final-syllable lexicality was a within-subjects variable, and task was a between-subjects variable. Only correct responses were analyzed. Latencies and accuracy scores for lexical decision and shadowing are shown in Table 3.

Latencies

The effect of task was significant: $F_s(1, 40) = 6.72, p < .02$; $F_i(1, 100) = 56.59, p < .0001$. Reaction times in the shadowing task were 100 ms faster than RTs in the lexical decision task. Neither the effect of final-syllable lexicality (both $Fs < 1$) nor the interaction, $F_s(1, 40) = 1.12, p > .29$, $F_i < 1$, was significant.

Table 3
Mean Response Latencies (in Milliseconds) and Percentages Correct for Experiment 2

	Stimuli							
	Word final				Nonword final			
Task	RT	*SE*	% correct	*SE*	RT	*SE*	% correct	*SE*
Lexical decision	1,069	33	92	1.0	1,071	28	89	1.6
Shadowing	975	25	96	0.9	965	24	96	0.8
Both	1,019	21	94	0.7	1,015	20	93	0.1

Note. RT = reaction time.

Accuracy

The effect of task was significant by participants, $F_s(1, 40) = 17.06, p < .0002$, but not by items, $F_i(1, 100) = 3.29$, $p > .07$. Accuracy was 5% lower in the lexical decision task than in the shadowing task. The effect of final-syllable lexicality was not significant by participants ($F_s < 1$) or by items, $F_i(1, 100) = 2.96, p > .09$, nor was the interaction ($F_s < 1.0$), $F_i(1, 100) = 2.96, p > .09$.

Discussion

In contrast to our findings for first-syllable embedded words, we obtained no significant effects of syllable lexicality for syllable-final embedded stimuli. Indeed, the overall magnitude of the effect of final-syllable lexicality on RTs was only 4 ms across the two tasks.

To establish the statistical interaction between the presence of effects of lexical embeddedness in Experiment 1 and their absence in Experiment 2, we combined the results from the two experiments into 2 three-way (Experiment × Task × Target Syllable Lexicality) ANOVAs: one for latencies and one for accuracy. The crucial interaction of experiment and target syllable was significant by participants and items for the latencies: $F_s(1, 82) = 21.77, p < .0001$; $F_i(1, 168) = 4.49, p < .04$. This same interaction was significant by participants for the accuracy scores only: $F_s(1, 82) = 4.52, p < .04$ ($F_i < 1$).

General Discussion

Previous experiments using the cross-modal priming and word-spotting techniques have demonstrated that embedded words may be activated when the carrier word is heard. However, previous research has not examined the effect of embedded words on recognition of the carrier word itself. Our results indicate that the presence of embedded words in the first syllable speeds processing of bisyllabic carrier words. Second-syllable embedded words have no measurable effect.

Our results parallel the findings of Taft and Forster (1976), who also found facilitatory effects of first-syllable embedded words in the visual modality but no effect of later occurring words. This aspect of the present results is also consistent with Swinney's (1981) minimal accretion principle, as well as with the predictions of TRACE and SHORTLIST regarding the effects of activation of later occurring embedded items. At first glance, however, our results do not appear consistent with some of the previous cross-modal priming results (e.g., Luce & Cluff, 1998; Vroomen & de Gelder, 1997) that suggest that words embedded in the second syllable of a carrier item may be activated during recognition. Although our findings demonstrate that there is apparently little or no effect of activation of second-syllable embedded words on processing times,

[2] Note that in this experiment, initial syllables were identical within a given stimulus pair.

they are not necessarily inconsistent with the notion that second-syllable embedded words may accrue some measure of activation during recognition. It is possible that second-syllable words are indeed activated, but recognition of the carrier word may be far enough along that activation of the second-syllable embedded word does not influence speed of processing. The findings from the present experiments—which demonstrate no effect of second-syllable embedded items on processing of the carrier word—and previous priming experiments—which demonstrate second-syllable lexical activation—are in fact consistent with the simulations of TRACE performed by Frauenfelder and Peeters (1990), which show that later occurring embedded items may be activated (albeit quite weakly) with no effects on activation of the carrier word.

It is clear, however, that our results do not directly parallel the data from word spotting, in which carrier and embedded words interfere with one another. These differences may be due, in part, to the experimental paradigms used. Lexical decision and shadowing measure processing of the carrier word rather than detection of the embedded word. Thus, the tasks used in the present study may be tapping different processes than those deployed in the word-spotting paradigm. In particular, actively searching for embedded lexical items may invoke quite different strategies than simply repeating back or deciding upon the lexicality of a target word.

In addition, the shadowing, lexical decision, and spotting tasks may be tapping the word-recognition process at different times. Both interference and facilitation may be operative in the recognition process, with processes responsible for interference dominating the recognition process at later stages of processing (see Vitevitch & Luce, 1998, in press). Thus, shadowing and lexical decision times may be more reflective of earlier processes in which embedded items play a facilitatory role. (Presumably, one could evaluate this hypothesis by comparing the RTs in the three tasks. However, direct comparison of RTs in these tasks is difficult because of the very high error rates in word spotting compared with the error rates in the shadowing and lexical decision tasks.)

Despite these discrepancies, our findings have potentially important implications for current models of word recognition. In simulations of the TRACE model, Frauenfelder and Peeters (1990) found that predicted recognition of carrier words was slowed when a word was embedded in the first syllable because of multiple activation of, and inhibition among, nodes at the word level. Our results conflict with this specific prediction. We found no evidence of interference between carrier and embedded words in initial position. In fact, only facilitatory effects for first-syllable embedded words were observed. If competition between carrier words and initial embedded items plays a role, it must occur relatively late in the word-recognition process and must not affect early processing of the carrier word itself. Note that we are not claiming that facilitatory effects are prelexical and that competition effects are postlexical. Instead, we propose that facilitatory effects due to initial embedding may dominate competition effects early in processing, ultimately speeding RTs in naming and lexical decision.

Thus, both facilitation and competition may characterize the effects of recognition of embedded lexical items. In Norris's (1994) SHORTLIST, inhibition arises in a second stage of processing, presumably later in the recognition process. Likewise, in a model such as TRACE, given appropriate tuning of relative connection strengths, excitatory feedback between levels may dominate early in the recognition process, thus giving rise to the observed effects of facilitation of embedded words on the processing of carrier words. That is, segments may pass activation to lexical nodes corresponding both to the carrier word and the initial embedded item. These lexical nodes may then pass activation back to the segment nodes, establishing a feedback loop that would afford activation advantages to words with initial embedded items. Note, however, that such a system will only produce advantages for lexically embedded items if inhibition at the lexical level does not overwhelm the effects of interlevel facilitation. Whether effects of interlevel facilitation and intralevel inhibition can actually be balanced to produce effects of both facilitation and competition remains to be seen.

The hypothesis that interference effects take time to develop is supported by a study by Vroomen and de Gelder (1995). They compared the activation of words embedded in two-syllable nonwords. They found that cross-modal priming effects were reduced when an embedded word has more lexical competitors. Most important, however, they found that when the delay between the prime and target is shortened, the difference in competitor-based interference disappears. Thus, effects of interference in Vroomen and de Gelder's (1995) study appear to be relatively slower in exerting their influence on the recognition process. Although admittedly brief, this delay may be sufficient to allow time for facilitatory effects to dominate early enough in the recognition process to produce the types of effects observed in the present experiments.

Another possible explanation of the present data may be that in the shadowing and lexical decision tasks, responses are initiated based either on the embedded word or the carrier word. Thus, the processing advantage for the word-initial stimuli may come from the fact that responses are initiated on the basis of the embedded word rather than the carrier itself. Subsequent recognition of the carrier word may either inherit the processing advantage of the embedded word through some as yet unspecified mechanism, or processing may simply shift from the representation of the embedded word to the representation of the carrier with no cost in time or effort.

Such an explanation is viable only if there is reason to expect an advantage of the embedded word over the matched nonword-initial stimulus. However, the embedded words in the word-initial stimuli were matched in duration to the nonword-initial syllables, thus affording no potential advantage based on stimulus duration. That is, the embedded initial item could not have been processed more quickly—on the basis of duration alone—than the first syllable of the matched nonword-initial stimulus. More important, the frequencies of the embedded words alone were not significantly higher ($F < 1$) than the overall frequency of the nonword-initial items. Thus, the embedded word could not have speeded processing because of frequency differences between carrier words and embedded words. The only apparent mechanism that could have given rise to the observed effects is the simultaneous activation of initial embedded items and carrier words in the absence of strong lateral inhibition effects among activated items, at least early in the recognition process.

The results of the present experiments have implications both for lexical segmentation and for models of spoken word recognition. The finding that final embedded items fail to show measurable effects on processing times for spoken carrier words is consistent with earlier proposals that state that the processing system prefers interpretations corresponding to longer words. This preference may result from implicit strategic processing or may be a consequence of lateral inhibition among competitors. Whatever the precise mechanism, it is becoming clear that, despite the now-compelling evidence for activation of lexically embedded items at the ends of carrier words (Luce & Cluff, 1998; Shillcock, 1990; Vroomen & de Gelder, 1997), the processing of longer carrier words appears to be unaffected by activation of later occurring items. These findings place further constraints on the radical activation hypothesis, suggesting at least one means by which the listener deals with the vexing problem of lexical segmentation in connected discourse.

The direct implications of the present findings for current models of spoken word recognition are less straightforward. Many current models of spoken word recognition—such as Norris's (1994) SHORTLIST model and Luce and Pisoni's (1998) neighborhood activation model—rely heavily on mechanisms of lexical competition to account for a variety of empirical phenomena (see also Goldinger, Luce, & Pisoni, 1989; Goldinger, Luce, Pisoni, & Marcario, 1992; McQueen et al., 1994; Norris et al., 1995). Clearly, the present results do not refute these mechanisms but do suggest a complex system in which simultaneous processes of facilitation and competition trade in the recognition process. Vitevitch and Luce (1998, in press) have suggested that segmental and lexical levels of processing may be distinguished by the degree to which they are dominated by facilitation and competition, with competition among lexical items considered to be the hallmark of lexical processing. It may well be that when lexical competitors share identical segments, as with embedded and carrier words, segmental processing may benefit from feedback from multiply-activated lexical nodes. Segmental nodes may then in turn share their activation advantages with the lexical nodes to which they are connected. Or, alternatively, responses may be driven off of either the lexical or the segmental levels, depending on current activation values at either level (see Cutler & Norris, 1979). If segmental activation dominates early in processing, the advantage afforded by lexical embeddedness may result—at least early on—in faster processing for carrier words with initially embedded items. These proposals are, of course, speculative. Continued modeling work within the context of explicit simulation models is necessary in order to determine if the requisite interplay of facilitation and competition can be accomplished within existing computational architectures.

In summary, our results both conflict with and corroborate previous proposals in the literature regarding the effects of lexically embedded items on spoken word recognition. The results of the present experiments demonstrating no effects of lexical embedding late in the carrier word are consistent with TRACE, SHORTLIST, cohort, and the minimal accretion principle and are inconsistent with radical activation accounts. Our results are not consistent, however, with models that afford a primary role to lateral inhibition among lexical items early in the recognition process. It appears instead that lexical embedding may actually facilitate the recognition process in its very early stages.

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Appendix A

Stimuli for Experiment 1

Word initial	Word final	Word initial	Word final
crochet	cliche	surface	preface
roman	famine	cherry	quarry
cherish	flourish	agent	regent
witness	harness	muggy	soggy
raven	heaven	merry	sorry
German	lemon	felon	talon
planet	minute	prairie	theory
lucid	placid	logic	tragic
countess	practice	colon	villain

Appendix B

Stimuli for Experiment 2

Word final	Nonword final	Word final	Nonword final
aloe	alloy[b]	emit	immerse[a]
balloon	baton[a]	imbed	impel[a]
chloride	chlorine[b]	impure	implore[a]
conceal	concise[a]	jumbo	jumble[b]
conceit	confide[a]	limbo	limber[b]
confine	condemn[a]	khaki	cackle[b]
conserve	convert[a]	meadow	medal[b]
content	conclude[a]	paring	parish[b]
default	deflate[a]	profound	profuse[a]
deduce	detain[a]	restrain	respond[a]
degrade	depict[a]	retrace	recline[a]
distress	disturb[a]	suspend	suspense[a]
detest	deprive[a]	submerge	submerse[a]

[a]Primary stress on second syllable. [b]Primary stress on first syllable.

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