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# Probabilistic Phonotactics and Neighborhood Activation in Spoken Word Recognition

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Recent work (Vitevitch & Luce, 1998) investigating the role of phonotactic information in spoken word recognition suggests the operation of two levels of representation, each having distinctly different consequences for processing. The lexical level is marked by competitive effects associated with similarity neighborhood activation, whereas increased probabilities of segments and sequences of segments facilitate processing at the sublexical level. We investigated the two proposed levels in six experiments using monosyllabic and specially constructed bisyllabic words and nonwords. The results of these studies provide further support for the hypothesis that the processing of spoken stimuli is a function of both facilitatory effects associated with increased phonotactic probabilities and competitive effects associated with the activation of similarity neighborhoods. We interpret these findings in the context of Grossberg, Boardman, and Cohen's (1997) adaptive resonance theory of speech perception.

*Key Words:* spoken word recognition; probabilistic phonotactics; neighborhood activation; adaptive resonance theory.

*Phonotactics* refers to the sequential arrangement of phonetic segments in morphemes, syllables, and words (Crystal, 1980; Trask, 1996). From one perspective, phonotactics may be thought of as a phonological grammar that describes the ordering of the basic units (i.e., phonetic segments), with sequences conforming to this grammar considered *phonotactically legal* (Malmkaer, 1991). Research in both linguistics and psycholinguistics has investigated the implications of this information for the representation and processing of spoken language.

Research on phonotactics in linguistics has examined the representations of various types of sequential constraints and segmental co-occurrence relations in syllables and words (Frisch, Broe, & Pierrehumbert, 1995; Greenberg, 1950; Harris, 1983; Kessler & Treiman, 1997; Lightner, 1965; Mayzner & Tresselt, 1962; 1965; Mayzner, Tresselt, & Wolin, 1965; Ringen, 1988; Zimmer, 1967). For example, analyses of adjacent phonetic segments in syllables in English have shown that there are stronger constraints on co-occurrences of vowels and final consonants than on co-occurrences of initial consonants and vowels (Fudge, 1969, 1987; Kessler & Treiman, 1997; see also Clements & Keyser, 1983, and Greenberg, 1950).

Research on phonotactics in psycholinguistics has focused on the mental representation and processing of phonotactic information in children and adults. Jusczyk, Frederici, Wessels, Svenkerud, and Jusczyk (1993) demonstrated that 9-month-old Dutch and American infants are able to discriminate between legal sequences of phonetic segments in their native language and illegal sequences from a foreign language. Jusczyk, Luce, and Charles-Luce (1994) have furthermore shown that 9-month-old infants are sensitive to the phonotactic con-

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figuration of nonwords *within* their native language. Using the headturn preference procedure, Jusczyk et al. demonstrated that infants attend longer to nonwords with common phonotactic patterns than to those with less common patterns. (See Messer, 1967, and Pertz and Bever, 1975, for discussions of phonotactic effects in older children.)

Research on adults has demonstrated similar sensitivities to phonotactic information. For example, Brown and Hildum (1956) presented three types of monosyllabic spoken items in noise for identification: (1) real English words, (2) phonotactically legal nonwords, and (3) phonotactically illegal nonwords. Both phonetically naive and sophisticated participants identified real words most accurately, followed by legal nonwords. Illegal sequences were identified least accurately. Eukel (1980) has also demonstrated that adults' subjective ratings of the possible frequencies of nonwords are a function of their phonotactic configuration.

Recently, psycholinguistic research on phonotactics has shifted from comparisons of phonotactically legal and illegal sequences to investigations of *probabilistic* phonotactic information. Probabilistic phonotactics refers to the relative frequencies of segments and sequences of segments in syllables and words. Using estimates of positional probabilities based on a computerized lexicon, Treiman, Kessler, Knewasser, Tincoff, and Bowman (1996) found that participants' performance on rating and blending tasks was sensitive to probabilistic differences among phonetic sequences. Participants in the rating task judged high probability patterns to be more "English-like" than low probability patterns (see also Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). In the blending task, when asked to combine two sound patterns into a single item, high probability sequences tended to remain intact more often than low probability sequences.

Vitevitch et al. (1997) examined the effects of probabilistic phonotactic information on *processing times* for spoken stimuli. They used bisyllabic nonwords composed of phonetic sequences that were legal in English but varied in their segmental and sequential probabilities. Using a speeded single-word shadowing task, Vitevitch et al. found that bisyllabic nonwords composed of common segments and sequences of segments were repeated faster than nonwords composed of less common segments and sequences.

Taken together, these studies demonstrate that information regarding the legality and probability of phonotactic patterns has demonstrable influences on the representation and processing of spoken stimuli (see also Massaro & Cohen, 1983). A potential anomaly has arisen, however: The effects of phonotactics demonstrated thus far seem to contradict the predictions of—and evidence for—a class of models that emphasize the roles of activation and competition in spoken word recognition (see Luce & Pisoni, 1998; Marslen-Wilson, 1989; McClelland & Elman, 1986; Norris, 1994).

One particular activation-competition model that is in direct contrast to Vitevitch et al.'s work on probabilistic phonotactics is the neighborhood activation model (NAM; Luce & Pisoni, 1998). This model claims that spoken words that sound like many other words (i.e., words in dense similarity neighborhoods) should be recognized more slowly and less accurately than words with few similar sounding words (i.e., words in sparse similarity neighborhoods). A contradiction is revealed by the observation that high probability segments and sequences of segments are found in words occurring in high density neighborhoods, whereas low probability segments and sequences of segments are found in words occurring in low density neighborhoods. Thus, NAM predicts that high probability phonotactic stimuli should be processed *more slowly* than low probability phonotactic stimuli, in contrast to the findings of Vitevitch et al.

In an effort to explore these seemingly contradictory results, Vitevitch and Luce (1998) presented participants in a speeded auditory shadowing task with monosyllabic words and nonwords that varied on similarity neighborhood density and phonotactic probability. They generated two sets of words and nonwords: (1) high phonotactic probability/high neighborhood density stimuli and (2) low phonotactic probability/low neighborhood density stimuli. Vitevitch and Luce (1998) replicated the pattern of results obtained in the Vitevitch et al. study for *nonwords:* High probability/density nonwords were repeated more quickly than low probability/density nonwords. The *words,* however, followed the pattern of results predicted by NAM. That is, high probability/density words were repeated *more slowly* than low probability/density words.

Vitevitch and Luce (1998) suggested that two levels of representation and processing—one lexical and one sublexical—are responsible for differential effects of phonotactics and neighborhoods. (The concept of these two levels of processing has, of course, a long history in the field. For previous similar proposals regarding levels of processing in spoken word recognition, see Cutler & Norris, 1979; Foss & Blank, 1980; McClelland & Elman, 1986; Norris, 1994; Radeau, Morais, & Segui, 1995; Slowiazcek & Hamburger, 1992.) In particular, Vitevitch and Luce (1998) suggested that facilitatory effects of probabilistic phonotactics might reflect differences among activation levels of *sublexical* units, whereas effects of similarity neighborhoods may arise from competition among *lexical* representations. (Slowiazcek and Hamburger make a similar argument on the basis of "phonological" priming data. However, their results must be interpreted with caution. See Goldinger, 1998a, b.) Models of spoken word recognition such as TRACE (McClelland & Elman, 1986), Shortlist (Norris, 1994), and NAM all propose that lexical representations compete with and/or inhibit one another (see Cluff & Luce, 1990; Goldinger, Luce, & Pisoni, 1989; Luce & Pisoni, 1998; Marslen-Wilson, 1989; McQueen, Norris, & Cutler, 1994; Norris, McQueen, & Cutler, 1995). Thus, words occurring in dense similarity neighborhoods succumb to more intense competition among similar sounding words activated in memory, resulting in slower processing. Apparently, effects of lexical competition overshadow any benefit these high-density words accrue from having high probability phonotactic patterns.

Because nonwords do not make direct contact with a single lexical unit, and thus do not immediately initiate large-scale lexical competition, effects of segmental and sequential probabilities emerge for these stimuli. That is, in the absence of strong lexical competition effects associated with word stimuli, higher activation levels of sublexical units (associated with higher phonotactic probabilities) afford advantage to high probability nonwords. Note that this account does not presume that lexical competition is entirely absent for nonwords, nor that facilitatory effects of phonotactics are inoperative for words. Instead, Vitevitch and Luce (1998) proposed that lexical competition dominates for words, whereas effects of phonotactics are the primary determinant of processing times for nonwords.

## A FRAMEWORK FOR PHONOTACTICS AND NEIGHBORHOOD ACTIVATION

To provide a more precise, mechanistic account of our original results, we adopt a framework based on Grossberg's adaptive resonance theory (ART) of speech perception (Grossberg, 1986; Grossberg, Boardman, & Cohen, 1997; Grossberg & Stone, 1986). A schematic diagram of this framework is shown in Fig. 1. Input activates *items* in working memory, which in turn activate *list chunks* in short-term memory. (Grossberg and Stone, 1986, equate working and short-term memory (see p. 59), although Grossberg et al. (1997) make a distinction—which we adopt here—between *items* in working memory and *lists* in short-term memory (see Figs. 1 and 2 in Grossberg et al., 1997)). Items are hypothesized to be composed of feature clusters; list chunks correspond to possible groupings of items, such as segments, subsyllabic sequences of segments, syllables, and words. Although Grossberg posits no explicit set of tiered processing levels among the representations in short-term memory, we use the terms *lexical* and *sublexical* throughout the ensuing discussion to refer to list chunks corresponding to words and their components, respectively.[1] For our purposes, two properties of

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[1] The notion of "levels," as typically embodied in such connectionist models as TRACE, is categorically rejected in Grossberg's model (see Grossberg, et al., 1997). We nonetheless use the term "level" throughout to refer to representations corresponding to lexical and sublexical representations. However, we do not assume that activation of sublexical units is a necessary prerequisite to activation of lexical units.

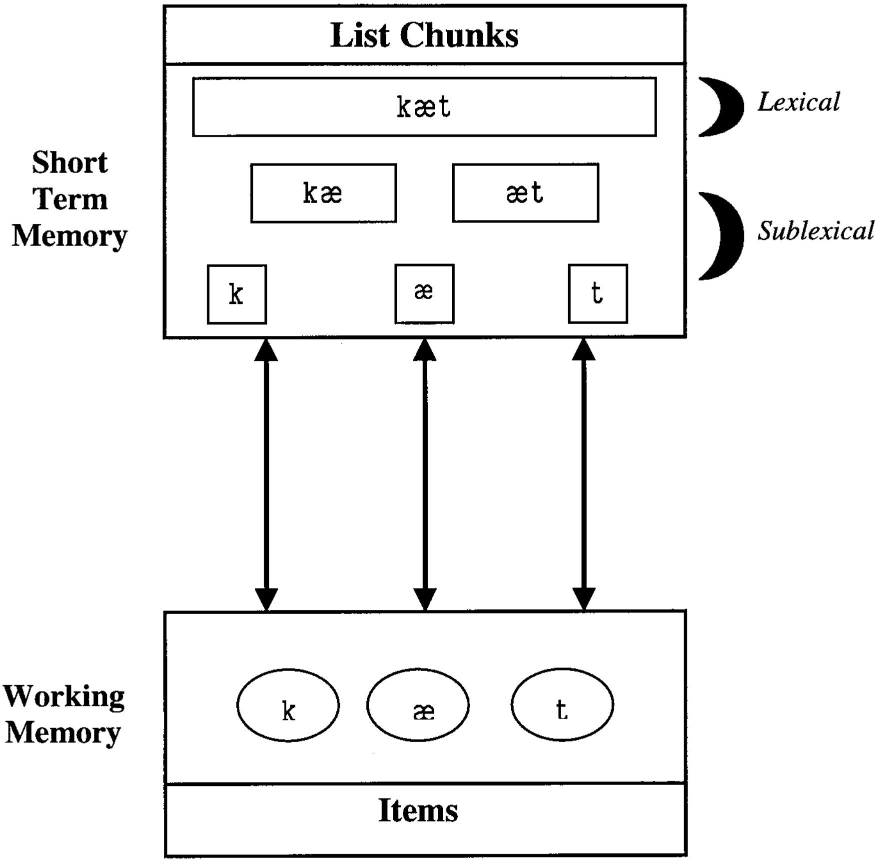

**FIG. 1.** A schematic diagram of a framework for spoken word recognition based on adaptive resonance theory (based on Grossberg, Boardman, & Cohen, 1997).

list chunks are of primary importance: (1) List chunks compete among one another via lateral inhibitory links and (2) longer list chunks "mask" or inhibit smaller sublist chunks (Grossberg et al., 1997).

Once matching list chunks receive signals from items in working memory, these list chunks send excitatory signals back to the items, establishing a *resonance* between list chunks in short-term memory and items in working memory (indicated in Fig. 1 by lines with double arrows). Typically, an equilibrated resonant state develops over time between the best-matching, most predictive list chunk and the items in working memory. This equilibrated resonant state constitutes the speech percept. According to Grossberg et al., "[s]uch resonant states, rather than the activations that are due to bottom-up processing alone, are proposed to be the brain events that represent conscious behavior" (p. 481). Thus, in this framework, responses are based on resonances between the most active list chunks and working memory items rather than on any specific "node" or representation at a particular level of processing.

Each of Vitevitch and Luce's (1998) four conditions is illustrated in Fig. 2 in the context of the adaptive resonance framework: (a) High probability/density words are represented by the word *cat,* (b) low probability/density words by *fish,* (c) high probability/density nonwords by the nonword /sʌv/, and (d) low probability/density nonwords by /jʌʃ/. Items are represented by circles and list chunks by rectangles. Resonances are represented by lines with double arrows. Lines ending in filled circles signify inhibitory signals impinging on the list chunk in

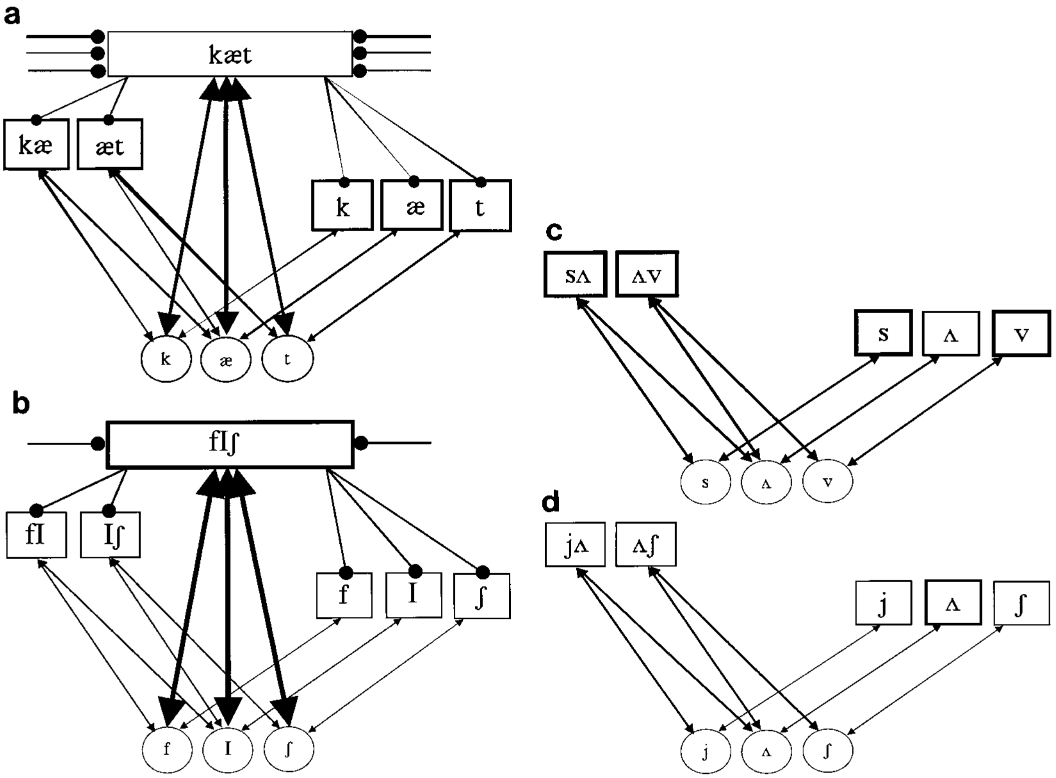

**FIG. 2.** Activation within the adaptive resonance framework for: (a) high probability/density words (e.g., *cat*), (b) low probability/density words (e.g., *fish*), (c) high probability/density nonwords (e.g., /sʌv/), and (d) low probability/density nonwords (e.g., /jʌʃ/). Only selected inhibitory and resonance connections are shown.

question. The sizes of the lines and terminators (for both resonant states and inhibitory signals) indicate the strength of the connection, and relative levels of activation for each list chunk are indicated by the boldness of the box. For clarity, only selected connections are shown (e.g., inhibitory links between sublexical units are assumed but not depicted).

Consider first the high probability/density word *cat.* Items in working memory are assumed to activate at least three different sized list chunks, corresponding to segments (e.g., /k/, /æ/, and /t/), sequences of segments (e.g., /kæ/ and /æt/), and the lexical items itself (/kæt/).[2] Because the word *cat* is a member of a high density neighborhood, multiple lateral inhibitory signals converge on this list chunk (indicated in Fig. 2 by the six inhibitory links terminating on the box labeled /kæt/). Despite lateral inhibition from competing lexical items, the chunk corresponding to *cat* nonetheless dominates the other activated lists in short-term memory, thereby establishing the strongest resonance with the items in working memory. The resonance between the chunk corresponding to *cat* and the items in working memory will determine the percept and hence the response.

The situation for the low probability/density

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[2] The phoneme labels for items and list chunks are used for convenience and are not to be construed as a theoretical assertion regarding the reality of these representations. Nor is the representation of the consonant–vowel and vowel–consonant list chunks necessarily meant to imply an independent representational status for these sublexical sequences. These labels are intended to represent clusters of co-occurring features. Whether these feature clusters constitute independent representational entities is, at present, unclear. In addition, the reader should bear in mind that subsequent computations of segmental and phonotactic probabilities do not imply a *theoretical* stance regarding the units used to carry out the computations.

word *fish* is much the same, with the list chunk corresponding to *fish* having the strongest resonance with items in working memory. However, owing to the smaller number of lateral inhibitory signals emanating from similar lexical items, the list chunk for *fish* is predicted to establish a stronger resonance than the resonant state that develops for a word in a high density neighborhood, resulting in faster predicted processing times. Thus, because of (1) lateral inhibitory connections among lexical list chunks and (2) the hypothesized masking effects of larger list chunks, the adaptive resonance framework predicts slower processing times for words in high density neighborhoods relative to those in low density neighborhoods (see Luce & Pisoni, 1998; Vitevitch & Luce, 1998).

The reversal of the effect of probability/density is illustrated in Fig. 2 for the high probability/density nonword /sʌv/ and the low probability/density nonword /jʌʃ/. Once again, input activates a set of items in working memory, which in turn activate list chunks. In the absence of any corresponding lexical item in memory for a nonword stimulus, the largest list chunks that will be strongly consistent with items in working memory will be those corresponding to segments and sequences of segments. Because activation levels of list chunks are assumed to be a function of frequency of occurrence, sublexical chunks for high probability/density stimuli such as /sʌv/ are predicted to establish stronger resonances with items in working memory than sublexical chunks for low probability/density stimuli such as /jʌʃ/. (See Grossberg & Stone, 1986, for a discussion of precisely how frequency information is encoded in the network.) Furthermore, given the absence of strongly activated lexical chunks that might mask or inhibit sublexical chunks, resonances between chunks corresponding to segments and sequences of segments determine processing times for nonwords.

Note that for nonwords, partially overlapping list chunks that correspond to lexical items are assumed to be transiently activated (although not illustrated in Fig. 2). However, resonances for these lexical list chunks will be weak, given that no lexical item will be completely consistent with the input.

Another reason that sublexical chunks dominate processing for nonwords (winning out over partially activated lexical chunks) is because attention is focused on those chunks that establish the strongest resonances, thereby further amplifying their connections with items in working memory (see Grossberg & Stone, 1986). Finally, top-down expectations may help determine the particular list chunk that dominates processing, thus affording advantage to sublexical list chunks when the processing environment (e.g., only nonwords are presented) or experimental task (e.g., phoneme identification or phoneme monitoring) encourages a level of analysis below the word (see below).

Despite our hypothesis that effects of probabilistic phonotactics are facilitatory and have their source at a sublexical level, whereas effect of neighborhood activation are competitive and lexical, we do not mean to imply that the two effects arise from fundamentally different processes operating on lexical and sublexical representations. Indeed, the only difference between the two “levels” is the size of the list chunks involved and, consequently, their differential roles in masking fields. For example, the advantage of high over low probability phonotactics is a form of frequency effect at the sublexical level in the same way that the advantage of common over rare words is an effect of frequency at the lexical level.

In short, adaptive resonance theory provides a useful framework for accounting for the differential effects of neighborhood density and probabilistic phonotactics within a well-articulated theoretical context. This framework is particularly attractive because it embodies general principles and mechanisms that are motivated by considerable modeling and empirical work in various perceptual domains (see Grossberg, 1986).

Our overall goal in the present investigation is to explore in more detail the processing of spoken stimuli based on lexical and sublexical list chunks in short-term memory. Because our original finding regarding the dissociation of phonotactics and density provides the impetus for the ensuing research, we first attempt to replicate the Vitevitch and Luce (1998) results using a different experimental methodology in order to place this effect on a firm empirical footing. We then turn to a more stringent test of our hypothesis by attempting to demonstrate that the processing of the *same* spoken stimuli may be based on *either* lexical or sublexical list chunks, depending on processing environment and task requirements. In particular, we attempt to create situations in which lexical processing is emphasized for nonwords and sublexical processing for words. If it is possible to focus processing on lexical and sublexical chunks, we should be able to induce differential effects of facilitatory probabilistic phonotactics and competitive neighborhood density in both words and nonwords, thus lending further support to the hypothesis that probabilistic phonotactics and similarity neighborhood density have effects at different levels of representation. In short, we attempt to make nonwords function in a more word-like manner (i.e., show diminished effects of probabilistic phonotactics) and words function more like nonwords (i.e., show diminished effects of lexical competition).

Another major goal is to explore phonotactics and neighborhood activation for longer, bisyllabic spoken stimuli. Longer stimuli pose an interesting test case for the current framework. All things being equal, longer list chunks require more input than shorter chunks to achieve equivalent levels of activation (see Grossberg, 1986). Moreover, it is possible to select longer spoken stimuli that require considerable input before they can be uniquely identified. Use of such stimuli will enable us to determine if sublexical chunks might, under certain circumstances, play a role in the processing of *real words.*

We reason that certain longer words might pose a short-term problem for establishing a dominant resonant state based on lexical chunks, for example, when lateral inhibition (density effects) play a prominent role throughout the recognition process. If processing can indeed be focused on either lexical or sublexical levels while attempting to recognize a longer spoken word, perhaps high probability sublexical chunks will exert demonstrable effects on recognition in instances in which lexically based resonances are slow to develop. Such a demonstration would help to identify circumstances in which sublexical representations might play a role in normal on-line spoken language processing. In short, bisyllabic stimuli enable us to examine the possible differential roles of probabilistic phonotactics and lexical density as they interact within a longer temporal processing window prior to establishment of a dominant resonant state.

## EXPERIMENT 1

Both Vitevitch et al. (1997) and Vitevitch and Luce (1998) used the single-word shadowing task to demonstrate that phonotactic probabilities based on segmental and sequential probabilities affect the processing of spoken stimuli. Although unlikely (see Levelt & Wheeldon, 1994), there is a possibility that at least a portion of the effect on reaction times observed in these studies is due to the time required to *produce* the stimuli. We therefore conducted a replication of the Vitevitch et al. study using a task with no speech production component, namely, the speeded same–different task. In this task, participants are presented with two spoken stimuli on a given trial and must respond as quickly and as accurately as possible if the two items are the same or different. We were interested in participants' reaction times to respond *same* as a function of phonotactic probability and density.

We again presented words and nonwords that varied simultaneously on phonotactic probability and neighborhood density. Stimuli were classified as either high on both phonotactic probability and neighborhood density (high probability/density) or low on both measures (low probability/density).[3] Based on our previous work, we predicted opposite effects of probability/density on words and nonwords. In particular, responses should be faster to high than low probability/density *nonwords*, thus exhibiting effects of probabilistic phonotactics. On the other hand, responses should be slower to high than low probability/density *words* because of increased competition among lexical neighbors.

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[3] The correlation between neighborhood density and probabilistic phonotactics is sufficiently high that selection of an adequate number of well-controlled stimuli that orthogonally vary on the measures is, at present, difficult.

## *Method*

### *Participants*

The participants in this and the following experiments were right-handed native speakers of American English, with no reported history of speech or hearing disorders. The eighteen participants were recruited from the University at Buffalo community and were paid $5. No participant took part in more than one experiment reported here.

### *Materials*

The 240 nonwords and 140 words used in Vitevitch and Luce (1998) were used in this experiment. The nonwords were also the same as those used in Jusczyk, Luce, and Charles-Luce (1994). (The numbers of nonwords and words differ because the stimuli were chosen in part to provide comparisons with bisyllabic stimuli used in subsequent experiments.)

*Phonotactic probabilities.* We used two measures to determine phonotactic probability: (1) positional segment frequency (i.e., how often a particular segment occurs in a position in a word) and (2) biphone frequency (i.e., segment-to-segment co-occurrence probability, which itself is almost perfectly correlated with segmental transitional probability; see Gaygen, 1998). These metrics were based on log-frequency-weighted counts of words in an on-line version of Webster's (1967) Pocket Dictionary, which contains approximately 20,000 computer-readable phonemic transcriptions.

Nonwords and words that were classified as high probability patterns consisted of segments with high segment positional probabilities. For example, in the high probability nonword /sʌv/ ("suv"), the consonant /s/ is relatively frequent in initial position and the consonant /v/ is relatively frequent in the final position. (Positional vowel probabilities were held constant across the two conditions because of the constraint that the five vowels /ʌ aɪ i e ɝ/ occur in equal proportions in each of the syllable types.) In addition, a high probability phonotactic pattern consisted of biphones with high probability initial consonant–vowel and vowel–final consonant sequences (e.g., /s/ followed by /ʌ/ and /ʌ/ followed by /v/ in the nonword /sʌv/).

Nonwords and words that were classified as low probability patterns consisted of segments with low segment positional probabilities and low biphone probabilities. Despite being relatively rare, none of the patterns were phonotactically illegal in English. Indeed, all segment positions and transitions in the nonwords occur in real English words. For the nonwords, the average segment and biphone probabilities were .1926 and .0143, respectively, for the high probability lists and .0543 and .0006 for the low probability lists. For the words, the average segment and biphone probabilities were .2013 and .0123 for the high probability lists and .1260 and .0048 for the low probability lists. The difference in the magnitudes of the segment and biphone probabilities reflects the fact that there are many more biphones than segments. A complete list of the stimuli can be found in Appendix A.

*Similarity neighborhoods.* Frequency-weighted similarity neighborhoods were computed for each stimulus by comparing a given phonemic transcription (constituting the stimulus word) to all other transcriptions in the lexicon (see Luce & Pisoni, 1998). A neighbor was defined as any transcription that could be converted to the transcription of the stimulus word by a one phoneme substitution, deletion, or addition in any position. The log frequencies of the neighbors were then summed for each word and nonword, rendering a frequency-weighted neighborhood density measure. The mean log-frequency-weighted neighborhood density values for the high and low density nonwords were 45 and 13, respectively. The neighborhood density values for the high and low density words were 56 and 40, respectively.

*Isolation points.* We determined isolation points (Marslen-Wilson & Tyler, 1980; see also Luce, 1986) using the transcriptions in the computerized lexicon. The mean isolation point was 2.98 phonemes for the high probability/density words and 2.93 phonemes for the low probability/density words ($F(1,138) = 1.59$, $p = .20$). All nonwords had isolation points at the final segment.

*Word frequency.* Frequency of occurrence (Kučera & Francis, 1967) was matched for the two probability/density conditions for the words. Average log word frequency was 2.59 for the low density/probability words and 2.68 for the high density/probability words ($F < 1$).

*Durations.* The durations of the stimuli in the two phonotactic conditions were equivalent. For the words, the high probability items had a mean duration of 664 ms and the low probability items had a mean duration of 653 ms ($F(1,138) < 1$). For the nonwords, the high probability items had a mean duration of 690 ms and the low probability items had a mean duration of 706 ms ($F(1,238) = 2.55$, $p = .11$).

The words and nonwords were spoken one at a time in a list by a trained phonetician. All stimuli were low pass filtered at 4.8 kHz and digitized at a sampling rate of 10 kHz using a 12-bit analog-to-digital converter. Stimuli were edited into individual files and stored on a computer disk.

### *Procedure*

Participants were tested individually. Each participant was seated in a booth equipped with a pair of Telephonics TDH-39 headphones and a response box. Presentation of stimuli and response collection was controlled by computer.

A trial proceeded as follows: A light at the top of the response box was illuminated to indicate the beginning of a trial. Participants were then presented with two of the spoken stimuli at a comfortable listening level. The interstimulus interval was 50 ms. Reaction times were measured from the onset of the second stimulus in the pair to the button press response. If the maximum reaction time (3 s) expired, the computer automatically recorded an incorrect response and presented the next trial. Participants were instructed to respond as quickly and as accurately as possible. *Same* responses were made with the dominant hand.

The words and nonwords were presented in separate lists. Order of list presentation was counterbalanced across participants. Half of the trials consisted of two identical stimuli (constituting *same* trials) and half of the trials consisted of different stimuli. Half of the *same* pairs had high phonotactic probabilities and half had low probabilities. Nonmatching stimuli were created by pairing stimulus items from the same phonotactic category. For the *different* stimulus pairs, items with the same initial phoneme and (when possible) the same vowel were paired.

Prior to the experimental trials, each participant received 10 practice trials. These trials were used to familiarize the participants with the task and were not included in the final data analysis.

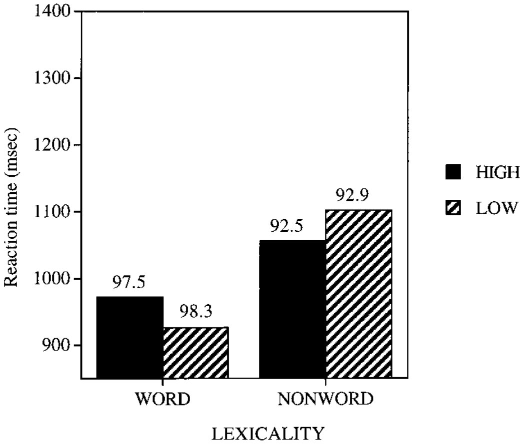

**FIG. 3.** Mean reaction times and percentages correct for the same–different matching task in Experiment 1. Results for words are on the left and for nonwords on the right. High probability/density stimuli are indicated by solid bars, and low probability/density by striped bars. The mean percentage correct is shown above the bar for each condition.

## *Results*

The mean reaction times in ms for correct *same* responses are shown in Fig. 3. Results are shown for both words and nonwords for each of the phonotactic/density conditions. Lexicality is plotted on the *x* axes.

Two (Lexicality) × 2 (Phonotactic Probability/Density) ANOVAs were performed for participants ($F_1$) and items ($F_2$) for both reaction times and percentages correct. Unless otherwise noted, a significance level of .05 was adopted. For the reaction times, words ($\bar{X} = 949$) were responded to significantly faster than nonwords ($\bar{X} = 1078$; $F_1(1,34) = 5.49$, $MSE = 55{,}296$ and $F_2(1,376) = 66.46$, $MSE = 19{,}161$). Although the main effect of probability/density was not significant (both $F$s $< 1$), a significant interaction of lexicality and probability/density was obtained ($F_1(1,34) = 19.02$, $MSE = 2040$, and $F_2(1,376) = 8.64$, $MSE = 19{,}161$).

Planned contrasts based on the significant interaction were performed to assess the effects of probability/density on the words and the nonwords separately. Low probability/density words ($\bar{X} = 926$) were responded to more quickly than high probability/density words ($\bar{X} = 972$; $F_1(1,17) = 10.94$ and $F_2(1,138) = 3.93$) and high probability/density nonwords ($\bar{X} = 1055$) were responded to more quickly than low probability/density nonwords ($\bar{X} = 1102$; $F_1(1,17) = 8.47$ and $F_2(1,238) = 6.65$). No significant effects were obtained for accuracy (all *F*s $< 1$).

### Discussion

The results of the same-different matching task replicate the findings of Vitevitch and Luce (1998): High probability nonwords were responded to more quickly than low probability nonwords, whereas the reverse effect was observed for words. Thus, the interaction of lexicality and phonotactic probability is not an artifact of the shadowing task.

Our definition of probabilistic phonotactics includes variation in positional probabilities of individual segments. Thus, high probability/density patterns may contain segments that do not occur in low probability/density patterns and vice versa. Although variations in positional segment frequency—and thus differences among segments themselves—were a focus of the present investigation, we were interested in determining if our effects crucially depend on the exclusive presence or absence of certain segments in the two probability/density conditions. Thus, we eliminated stimulus items in each condition that contained segments that were not common to both the high and low probability/density stimuli, rendering two stimulus sets sharing identical segments overall. For the nonwords, the average segment and biphone probabilities were .1550 and .0050, respectively, for the high probability lists and .0720 and .0010 for the low probability lists. Density values were 41 for the high condition and 15 for the low condition. For the words, the average segment and biphone probabilities were .2000 and .0120 for the high probability lists and .1290 and .0050 for the low probability lists. Density values were 52 for the high condition and 42 for the low condition. The words were also matched on log frequency (high = 2.57, low = 2.62; $F < 1$). Analyses performed on the reaction times for this subset of stimuli revealed significant effects for both the words ($F_1(1,17) = 9.88$, $MSE = 1832$, and $F_2(1,110) = 3.82$, $MSE = 9475$) and the nonwords ($F_1(1,17) = 8.98$, $MSE = 9834$, and $F_2(1,109) = 4.11$, $MSE = 28{,}619$), indicating that particular segments in the two sets of stimuli were not the sole source of the observed effects.

The current findings lend further support to the hypothesis that the effects of probabilistic phonotactics operate in different ways depending on the level of representation that dominates processing. Nonwords—which apparently fail to invoke strong competition among lexical items—benefit from higher probability segments and sequences of segments. Word stimuli, on the other hand, show the well-documented effects of lexical competition.

## EXPERIMENT 2

Having replicated the original findings of Vitevitch and Luce (1998), we now turn to a more specific test of the adaptive resonance framework. As previously stated, Grossberg's model allows for differently sized list chunks in short-term memory to establish dominant resonances depending on various factors, including attentional focus, expectancy, and the ability of the chunk to match the input (Grossberg, 1986). Thus, the model predicts that the level (i.e., lexical or sublexical) of the list chunk that dominates processing may be affected by characteristics of the processing environment. In particular, it should be possible to manipulate the degree to which words and nonwords are processed based on lexical and sublexical chunks.

Experiments 2 and 3 were designed to test this hypothesis. In Experiment 2, we again presented words and nonwords varying in probability/density for speeded same–different judgments. However, instead of presenting the word and nonwords in separate blocks (as in Experiment 1), we intermixed the two sets of stimuli. We hypothesized that participants would adopt a fairly consistent strategy for making their judgments on most trials, focusing on either the sublexical of lexical levels in order to accomplish the task. We furthermore hypothesized that the optimal strategy for performing the same–different judgment task with intermixed stimuli would be one in which participants focused on the level of representation common to both sets of stimuli, namely, the sublexical level. Thus, we predicted that we would still observe effects of probabilistic phonotactics for the nonwords. However, we also predicted that effects of lexical competition would be diminished for the words.

## *Method*

### *Participants*

Forty participants were recruited from the Indiana University Introductory Psychology pool and received partial credit for a course requirement.

### *Materials*

One-hundred and forty nonwords (70 from the high probability/density condition and 70 from the low probability/density condition) were randomly selected from the 240 nonwords used in Experiment 1. The *same* 140 real word stimuli used in Experiment 1 were also used in this experiment. Phonotactic probabilities, similarity neighborhoods, isolation points, word frequency, and stimulus durations for the words are given in Experiment 1. For the nonwords, the average segment and biphone probabilities were .1611 and .0055 for the high probability/density nonwords and .0571 and .0010 for the low probability/density nonwords. Mean log-frequency-weighted neighborhood density was 41 for the high nonwords and 12 for the low nonwords. Mean stimulus duration was 688 ms for the high nonwords and 717 for the low nonwords ($F(1,138) = 2.58$, $p = .11$). All isolation points for the nonwords were at the final segment.

### *Procedure*

The procedure was the same as Experiment 1 except for the following: (1) Beyerdynamic DT-100 headphones were used and (2) words and nonwords were randomly intermixed and presented in the same list, rather than being blocked by lexicality.

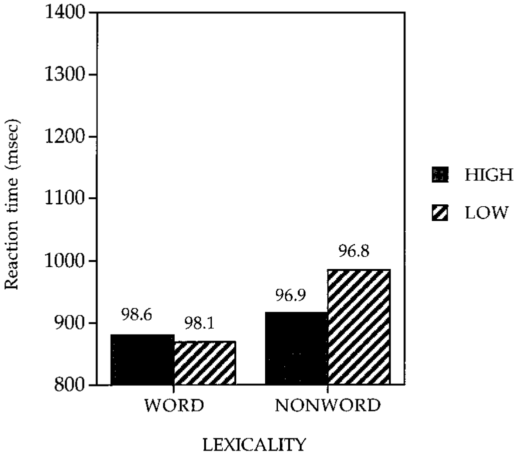

**FIG. 4.** Mean reaction times and percentages correct for the lexical decision task in Experiment 2. Results for words are on the left and for nonwords on the right. High probability/density stimuli are indicated by solid bars and low probability/density by striped bars. The mean percentage correct is shown above the bar for each condition.

## *Results*

The mean reaction times in ms for correct *same* responses are shown in Fig. 4. Two (Lexicality) × 2 (Phonotactic Probability/Density) ANOVAs were performed. For the reaction times, words ($\bar{X} = 875$) were responded to significantly faster than nonwords ($\bar{X} = 950$; $F_1(1,39) = 91.19$, $MSE = 2482$, and $F_2(1,276) = 34.75$, $MSE = 11{,}859$). Although an overall effect of probability/density was obtained in which high probability/density items ($\bar{X} = 899$) were responded to significantly faster than low probability/density items ($\bar{X} = 927$; $F_1(1,39) = 6.89$, $MSE = 4522$, and $F_2(1,276) = 4.15$, $MSE = 11{,}859$), the interaction of lexicality and probability/density was also significant ($F_1(1,39) = 29.86$, $MSE = 2202$, and $F_2(1,276) = 6.88$, $MSE = 11{,}859$).

Planned contrasts based on the significant interaction were performed to assess the effects of probability/density on the words and the nonwords separately. There was no difference between low probability/density words ($\bar{X} = 869$) and high probability/density words ($\bar{X} = 881$; $F_1(1,39) = 1.44$, $p > .10$, and $F_2(1,276) < 1$). However, high probability/density nonwords ($\bar{X} = 916$) were responded to more quickly than low probability/density nonwords ($\bar{X} = 984$; $F_1(1,39) = 42.58$ and $F_2(1,276) = 10.85$).

For accuracy, words were responded to more accurately than nonwords ($F_1(1,39) = 14.01$, $MSE = .001$, and $F_2(1,276) = 10.28$, $MSE = .001$). No other effects were found for accuracy (all $F\text{s} < 1$).

As in Experiment 1, we performed analyses on the reaction times for a subset of stimuli with matching segments. For the nonwords, the average segment and biphone probabilities were .1650 and .0050, respectively, for the high probability lists and .0740 and .0010 for the low probability lists. Density values were 44 for the high condition and 12 for the low condition. For the words, the average segment and biphone probabilities were .2000 and .0120 for the high probability lists and .1280 and .0050 for the low probability lists. Density values were 52 for the high condition and 42 for the low condition. The words were also matched on log frequency (high = 2.57, low = 2.62; $F < 1$). The crucial interaction of lexicality and probability/density was significant for reaction times when the stimuli were matched on segmental composition ($F_1(1,19) = 20.56$, $MSE = 1206$, and $F_2(1,169) = 7.83$, $MSE = 11,719$).

### *Discussion*

The results of Experiment 2 are consistent with the hypothesis that the lexical and sublexical levels may be differentially emphasized in the processing of spoken stimuli. In particular, the present data show that robust effects of neighborhood density (demonstrated in Experiment 1) can be substantially attenuated for the *same set of words* when the task environment emphasizes sublexical processing.

Although we obtained the predicted diminution of the effect of lexical competition for words intermixed with nonwords, we did not observe an actual reversal of the probability/density effect. That is, high probability/density words were *not* responded to more quickly than low probability/density words. This result was not unexpected. We hypothesize that the reduction of the density effect for words arose because on some significant portion of the trials, responses at the termination of stimulus input were based on sublexical resonances. However, the overarching advantages typically enjoyed by lexical chunks (e.g., lexical chunks are overall more predictive of the total input for words; lexical chunks are longer and thus mask sublexical chunks) enabled lexical resonances to prevail on a sufficient number of trials to offset the facilitatory effects of sublexical resonances on the remaining trials. In short, the reaction times for the words in this experiment appear to reflect the operation of both facilitatory phonotactics and lexical competition. Even though the reaction times for the words did not show a complete reversal, these results are nonetheless consistent with the proposal that sublexical and lexical effects may be traded off against one another for words. We now turn to Experiment 3, in which we attempt to induce effects of lexical activation on the processing of nonwords.

## EXPERIMENT 3

Neither shadowing (as in Vitevitch & Luce, 1998) nor speeded same–different matching necessitate activation of lexical representations in order to perform the task. Although we assume that when real word stimuli are processed, they will primarily activate their corresponding lexical representations in memory, conditions such as those in Experiment 2 can be created to bias against this chief mode of processing. A further test of the proposed framework involves the lexical processing of nonwords. In both shadowing and same–different matching, responses can be made to nonwords without actually activating lexical representations in memory. If our hypothesis is correct that nonwords are processed primarily at a sublexical level, encouraging lexically based processing for nonwords should reverse the effects of probabilistic phonotactics. To this end, we presented the words and nonwords in a lexical decision task.

We reasoned that because lexical decision requires discrimination between words and nonwords, nonword decisions should involve assessment of lexical activation. More specifically, we propose that high probability/density nonwords will activate many similar words in memory. Because the lexical decision task requires participants to discriminate between words and nonwords, the more words that are activated in memory, the slower the nonword response. We therefore predict a reversal of the pattern of results observed in the shadowing and same–different matching tasks: high probability/density nonwords in the lexical decision task should produce longer reaction times than the low probability/density stimuli.

## *Method*

### *Participants*

Twenty participants were recruited from the University at Buffalo community and were paid $5.

### *Materials*

One list of 240 words and 240 nonwords was constructed. The 240 nonwords were those used in Experiment 1. The 240 words consisted of the 150 words used in Vitevitch and Luce (1998). An additional 90 real words were used as filler items. Half of the words and nonwords were high in phonotactic probability and half were low. The filler items were prepared in the same manner as the experimental stimuli. Phonotactic probabilities, similarity neighborhoods, isolation points, word frequency, and stimulus durations for the nonwords are given in Experiment 1. For the words, the average segment and biphone probabilities were .1969 and .0118 for the high probability/density words and .1257 and .0050 for the low probability/density words. Mean log-frequency-weighted neighborhood density was 50 for the high words and 35 for the low words. Mean stimulus duration was 654 ms for the high words and 644 for the low words ($F(1,148) < 1$). Mean isolation point was 2.96 for the high words and 2.90 for the low words ($F(1,148) = 1.79$, $p = .1828$).

### *Procedure*

Participants were tested individually or in groups no larger than three. Each participant was seated in a booth equipped with a response box and a pair of Telephonics TDH-39 headphones. A PDP 11/34 computer was used to present stimuli and collect responses.

A typical trial proceeded as follows: A light on the top of the response box was illuminated to indicate the beginning of a trial. Participants were presented with one of the stimulus items over headphones at a comfortable listening level and responded by pressing one of the labeled buttons (*word* or *nonword*) on the response box. Reaction times were measured from the onset of the stimulus to the button press response. If the maximum reaction time (3 s) expired, the computer automatically recorded an incorrect response and presented the next trial. Participants were instructed to respond as quickly and as accurately as possible. After recording the response, the computer began another trial. Only responses made with the dominant hand were examined. Ten participants responded *word* and another 10 responded *nonword* with their right hands.

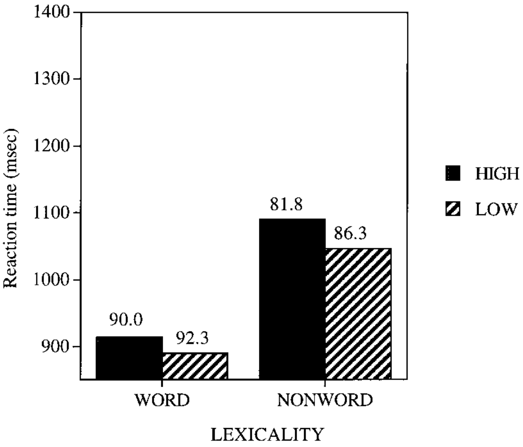

**FIG. 5.** Mean reaction times and percentages correct for the lexical decision task in Experiment 3. Results for words are on the left and for nonwords on the right. High probability/density stimuli are indicated by solid bars and low probability/density by striped bars. The mean percentage correct is shown above the bar for each condition.

Prior to the experimental trials each participant received 10 practice trials. These trials were used to familiarize the participants with the task and were not included in the final data analysis. Following practice, each participant received the 480 randomly ordered stimuli.

## *Results*

The mean reaction times in ms for correct responses are shown in Fig. 5. Two (Lexicality) × 2 (Phonotactic Probability/Density) ANOVAs were performed. Overall, low probability/density stimuli ($\bar{X} = 968$) were responded to more quickly than high probability/density stimuli ($\bar{X} = 1002$; $F_1(1,18) = 13.40$, $MSE = 878$, and $F_2(1,386) = 13.90$, $MSE = 12{,}622$), and words ($\bar{X} = 902$) were responded to more quickly than nonwords ($\bar{X} = 1068$; $F_1(1,18) = 7.10$, $MSE = 878$, and $F_2(1,386) = 177.67$, $MSE = 12{,}622$). There was no interaction of lexicality and probability/density (both $F$s $< 1$).

Low probability/density stimuli were also responded to more accurately than high probability/density stimuli ($F_1(1,18) = 9.81$, $MSE = .001$, and $F_2(1,386) = 6.16$, $MSE = .025$), and word responses were more accurate than nonword responses ($F_1(1,18) = 4.72$, $MSE = .020$, and $F_2(1,386) = 16.55$, $MSE = .025$). There was no interaction of lexicality and probability/density for the accuracy scores (both $F$s $< 1$).

We again performed analyses on the reaction times for a subset of stimuli with matching segments. For the nonwords, the average segment and biphone probabilities were .1550 and .0040, respectively, for the high probability lists and .0720 and .0010 for the low probability lists. Density values were 41 for the high condition and 15 for the low condition. For the words, the average segment and biphone probabilities were .2000 and .0120 for the high probability lists and .1280 and .0050 for the low probability lists. Density values were 52 for the high condition and 42 for the low condition. The words were also matched on log frequency (high = 2.57; low = 2.62, $F < 1$). When the stimuli in each of the probability/density conditions were matched on segmental composition, significant effects for reaction times were again obtained for lexicality ($F_1(1,18) = 7.37$, $MSE = 38{,}603$, and $F_2(1,217) = 119.70$, $MSE = 10{,}634$) and probability/density ($F_1(1,18) = 16.72$, $MSE = 1418$, and $F_2(1,217) = 8.29$, $MSE = 10{,}634$).

### *Discussion*

The results of Experiment 3 replicate the results of Vitevitch and Luce (1998) and Experiment 1 for the *words:* High probability/density words were responded to more slowly and less accurately than low probability/density words. However, high probability/density *nonwords* were also responded to more slowly and less accurately than low probability/density nonwords, in contrast to the results obtained in Experiments 1 and 2. As predicted, the lexical decision task produces similarity neighborhood effects for *both* words and nonwords. The differential effects on reaction time of probability/density (high and low), lexicality (word and nonword), and experiment (1, 2, and 3) resulted in a significant three-way interaction ($F_1(2,65) = 6.09$, $MSE = 1908$, and $F_2(2,1046) = 4.05$, $MSE = 14{,}733$).

Accounting for effects of phonotactics and neighborhood activation in the context of the proposed framework is fairly straightforward: Words in high density neighborhoods are subject to a greater degree of competition among lexical chunks than words in low density neighborhoods, resulting in slower response times in the lexical decision task. We propose that the reversal of the facilitatory effects of phonotactics for nonwords arises because of the nature of the lexical decision response itself. Luce and Pisoni (1998; see also Coltheart, Davelaar, Johansson, & Besner, 1976; Grainger & Jacobs, 1996) discuss an account of lexical decision in which responses may be based on two different sources of information, depending on self-imposed response-time deadlines adopted by participants in this speeded task. According to this account, a response may be initiated when activation for a unique lexical item has reached some criterion or threshold. However, when a single lexical item fails to receive sufficient activation within the time period required for a response, decisions may be based on the overall level of lexically based activity in the recognition system. This account of the lexical decision process is consistent with the pattern of results obtained for both the words and nonwords. For the words, responses were fastest when there was little lexical competition (i.e., when a single lexical item could be isolated relatively quickly). For nonwords, those with high probability/high density patterns—which presumably initiate large-scale lexical activity without engaging a *single* lexical item—were responded to more slowly than nonwords with low probability/density patterns.

In terms of our adaptive resonance framework, we hypothesize that strong resonances are quickly established for words between matching individual lexical chunks and the input, resulting in lexical decision responses based on the resonance for the target word presented.

Again, because of lateral inhibition among lexical chunks, resonances for high density words will be weaker than those for low density words, slowing processing for the high density items. For nonwords, however, multiple partial lexical resonances for stimuli in high density neighborhoods will delay nonword responses. We propose that because this task requires focus to lexically driven resonant states in order to make the word–nonword decision, increased activity emanating from lexical chunks slows nonword responses. Although the strongest resonances for the nonwords should still be established based on *sublexical* chunks, the nature of the lexical decision task should require focus of processing to shift to the weaker *lexical* chunks, where effects of lexical competition (i.e., neighborhood effects) on the discrimination process should arise.

Experiments 1–3 establish that effects of probabilistic phonotactics and neighborhood density emanate from different levels of processing (or, more precisely, different sized list chunks in short-term memory). In addition, we have demonstrated that the processing environment (e.g., intermixed words and nonwords) and task (e.g., lexical decision) may differentially affect the degree to which the sublexical and lexical levels dominate processing. We should note here that the degree to which lexical processing for words can be manipulated appears to be restricted to certain tasks, such as the same–different paradigm employed here. Although words and nonwords were mixed in the lexical decision task, the magnitude of the density effects was comparable to that observed in the naming task used by Vitevitch and Luce (1998) in which presentation of words was blocked. Moreover, Charles-Luce and Luce (1996) have shown that mixing words and nonwords in a naming task still results in significant density effects for words. However, mixing words and nonwords in the same–different task diminished the degree of lexical competition for the words. Thus, lexical effects appear to dominate for words in naming and lexical decision regardless of the stimulus context. We propose that tasks such as lexical decision and naming are most easily accomplished for words via the activation of lexical representations in memory. For naming, motor codes for production responses may be most readily accessible through contact with lexical representations. For lexical decision, recognition of a single word is most certainly the most rapid and accurate means of deciding on the lexicality of a stimulus. In same–different matching, on the other hand, lexical activation may be less crucial given that the task requires at most low-level matching of two acoustic patterns. Thus, certain tasks may be more amenable to manipulation of lexical effects for words than others.

So far, we have restricted our focus to short, monosyllabic words. We now turn our attention to an investigation of the effects of probabilistic phonotactics and neighborhood density on specially constructed bisyllabic stimuli. As we discussed in the Introduction, the adaptive resonance framework suggests that sublexical and lexical effects on the processing of spoken words may interact in interesting and nonintuitive ways when longer stimuli are examined. According to adaptive resonance theory, all things being equal, longer list chunks require more input to exceed threshold and establish an equilibrated resonance than shorter list chunks. Given the expanded time window required for a longer lexical chunk to establish a dominant resonance, we predict that effects of sublexical resonances not *normally* observed for short stimuli may play a more pronounced role in processing. Examination of processing of longer stimuli as a function of phonotactics and density may provide information regarding potential interactions among sublexical and lexical effects over time.

## EXPERIMENT 4

Vitevitch et al. (1997) presented specially constructed bisyllabic[4] nonwords that varied on phonotactic probability in a shadowing task. They found that nonwords composed of two

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[4] Throughout the discussion of Experiments 4, 5, and 6, we refer to our stimuli as "bisyllabic." Although all of the stimuli employed in these experiments do indeed consist of two syllables, the reader should bear in mind that the stimuli that we employ are special instances of two-syllable words and nonwords. We do not intend to imply that the results obtained for the stimuli in these experiments will necessarily generalize to *all* spoken bisyllabic items.

high probability syllables (hereafter referred to as high–high) were repeated more quickly and accurately than nonwords composed of two low probability syllables (low–low). Nonwords with one high and one low probability syllable (high–low and low–high) were repeated more slowly and less accurately than nonwords consisting of two high probability syllables, but more quickly and accurately than nonwords consisting of two low probability syllables. These results suggest that for bisyllabic nonwords, effects of phonotactic probability on shadowing times appear to emanate from the sublexical level.

We further examined the effects of phonotactic probability on shadowing times by (1) attempting to replicate the effect obtained by Vitevitch et al. (1997) and (2) examining bisyllabic real words. The bisyllabic nonwords were identical to those used in Vitevitch et al. except that primary stress for all stimuli fell on the first syllable. The bisyllabic *words* were composed of the syllables used in Experiments 1–3. The word stimuli employed in this and subsequent experiments were specially constructed compound words (e.g., madcap, catfish, hemline, and dishrag). We chose this special class of bisyllabic words for three reasons: First and foremost, by using bisyllabic stimuli composed of the monosyllabic stimuli in Experiments 1–3, direct comparison of the effects of phonotactics and neighborhood activation across the two sets of stimuli was possible. Second, by using the stimuli from the previous three experiments, we were able to orthogonally combine syllables of different probability/density. Third, use of compound words enabled precise control and manipulation of stress, phonotactics, and neighborhood density of the component syllables, a crucial requirement for tests of the hypotheses under scrutiny.

Within the context of the adaptive resonance framework, our predictions for the bisyllabic *nonwords* are straightforward: Shadowing responses should be driven by sublexical chunks. Moreover, the effects of probability/density as a function of syllable should be roughly additive: Two high probability/density syllables should produce the fastest response times, whereas two low probability/density syllables should result in the slowest responses. Mixed-syllable stimuli should produce intermediate processing times.

Our predictions for the *word* stimuli are somewhat more complex and provide a more interesting test of the proposed framework. Because of the bisyllabic words used in our experiments contained two syllables that are themselves words, lexical chunks should be activated in short-term memory that correspond both to the target word as a whole and to the component syllables. This particular configuration will enable us to examine in some detail the nature of lexical processing as a function of focus of processing and resonances based on variously sized list chunks.

We envision two possible scenarios for the word stimuli. In the simplest case, the pattern of results may be a mirror image of those obtained by Vitevitch et al. (1997) for bisyllabic nonwords: low–low words responded to most quickly, high–high least quickly, and high–low and low–high words producing intermediate response times. Such a pattern of results would follow directly from an additive combination of the effects of density across the two syllables. This scenario would result from a situation in which *only* effects of lexical processing are in evidence, with no demonstrable influence of sublexical chunks on recognition (i.e., no effects of probabilistic phonotactics).

However, given that we have established that the focus of processing may vary between lexical and sublexical levels—even for words—we propose a second possible scenario: First, we assume once again that the equilibrated resonance for the largest possible list chunk corresponding to the target word itself (e.g., “catfish”) will take a relatively long period of time to become established. In particular, we predict that the resonance for the target word itself will not begin to take form until after the onset of the second syllable, given that the lexical chunk corresponding to the first syllable (e.g., “cat” in “catfish”) will initially be the preferred interpretation (owing, in part, to the frequency advantage of the shorter embedded words over the longer target words).

Because an equilibrated resonant state based on the target word will be slow to develop, we foresee the opportunity for effects of both lexical and sublexical resonances to manifest themselves. Consider first the low–low words. In this case, strong resonances based on lexical chunks corresponding to both syllables will be established due to the relative lack of lexical competition arising from the low density component syllables. These strong lexical resonances will reinforce item nodes in working memory which will subsequently pass their activation to the larger list chunk corresponding to the target. In other words, the chunk corresponding to the target word (e.g., “dishrag”) will inherit the results of the strong resonances established by the low density component syllables (e.g., “dish” and “rag”).

A crucial aspect of this account is that the focus of processing will remain at the level producing the strongest resonance throughout recognition of the target word. According to Grossberg (1986), processing can be focused in a manner that “selectively sensitize[s] some internal representations more than others” (p. 265). We propose that lexical *or* sublexical chunks can be emphasized during the processing of multisyllabic words based on the “level” of processing that initially proves most predictive. We assume that focus of processing will be drawn to those chunks that have proven most successful over the course of processing (see Grossberg & Stone, 1986). Because resonant states for lexical chunks corresponding to the bisyllabic target words as a whole will be established relatively slowly, sublist chunks (i.e., sublexical chunks or lexical chunks corresponding to the component syllables) may dominate processing until the chunk for the complete target word has assumed priority. The resonant state corresponding to the lexical chunk for the bisyllabic target word as a whole will be slow to develop for at least two reasons: (1) The chunks corresponding to the bisyllabic word will be lower in frequency than its sublexical and lexical components and (2) “more . . . items need to be presented to activate a long-list node than a short-list node” (Grossberg, 1986, p. 270). In short, for low–low words, strong resonances between lexical chunks established early in the recognition of the target word will dominate processing until the chunk corresponding to the bisyllabic word itself establishes the strongest resonance.

This account also predicts that low–high words will produce slower response times relative to the low–low stimuli. Like the low–low stimuli, low–high words will initially engage strong resonances based on lexical chunks. Given our assumption that processing will be focused on the level of chunk that produces the strongest resonances early in recognition, processing at the initially successful lexical level will be slowed once the second, high density syllable is encountered, owing to heightened lexical competition for the second syllable. In short, this scenario predicts that reaction times for low–high words will be longer than those for low–low words (i.e., low–high $>$ low–low).

Now consider the high–low and high–high words. In these circumstances, sublexical resonances will be strong during processing of the initial syllable because of the high phonotactic probability of the first syllable and reduced masking by the larger lexical chunks in high density neighborhoods. We propose that continued input during the second syllable of longer words enables a given level of processing to assume dominance over the course of processing the stimulus. Thus, if strong resonances based on lexical chunks are established during the first syllable, focus of processing at that level will dominate. Alternatively, if strong sublexical resonances develop, they too will have the opportunity to control the focus of processing throughout the remainder of the longer stimulus word. For high–high and high–low words, therefore, strong sublexical resonances will be in evidence at the onset of the second syllable.

The result of these complex interactions among chunks in short-term memory is that focus of processing for high–high and high–low words may be at the sublexical level during processing of the onset of the second syllable. For high–high words, high phonotactic syllables in both positions will provide a processing *advantage.* However, processing for high–low words will be tuned to a less predictive level for processing of the second syllable, thus producing slower responses. In short, we predict that words with two high probability syllables will actually be processed more quickly than words with initial high and final low probability syllables (i.e., high–high $<$ high–low).

To summarize, our second scenario predicts that high–high and low–low word stimuli will both be processed relatively quickly, because each class of stimuli have a single level that will dominate throughout recognition. Low–low word stimuli will benefit from a lack of lexical competition, whereas high–high stimuli will accrue advantage through heightened probabilistic phonotactics. Under this scenario, the two mixed cases (high–low and low–high) should produce the longest response times.

## *Method*

### *Participants*

Forty participants were recruited from the University at Buffalo community and were paid $5.

### *Materials*

The monosyllabic stimuli used in Experiments 1–3 were combined to form 120 CVC-CVC bisyllabic words and 120 CVCCVC bisyllabic nonwords. The nonwords were the same as those used in Vitevitch et al. (1997) and were formed by combining the 240 nonsense syllables of varying phonotactic probability used in Jusczyk, Luce, and Charles-Luce (1994). For the nonwords, no syllable was used more than once.

*Words.* The 120 words were equally divided among four phonotactic conditions created by orthogonally combining phonotactic probability/density (high and low) and syllable position (initial and final). The four conditions were: high–high (high probability/density first syllable–high probability/density second syllable), high–low, low–high, and low–low. Note that frequency-weighted neighborhood density was defined for the *component syllables* of the words and nonwords. Previous research (Cluff & Luce, 1990; see also Charles-Luce, Luce, & Cluff, 1990) has demonstrated that neighborhood density has predictable effects on *both* syllables for bisyllabic stimuli. The results of Vitevitch et al. and Luce and Cluff (1998) also demonstrate that component syllables make separable contributions to the recognition of bisyllabic stimuli. Again we chose to compute similarity neighborhoods over the component syllables primarily because the syllables themselves constituted the stimuli in Experiments 1–3, thus allowing for fairly direct comparisons of the mono- and bisyllabic stimuli. In addition, the particular metric used for computing similarity neighborhoods produces very sparse neighborhoods when computed over longer, bisyllabic items. A complete list of the words can be found in Appendix B.

Segment and biphone probabilities of the component syllables were .1978 and .0121 for the high probability/density syllables and .1258 and .0051 for the low probability/density syllables. The following variables were equated for the word stimuli across the four conditions: stimulus duration ($F(3,116) = 1.93$, $p > .05$; high–high = 876; high–low = 903; low–high = 891; low–low = 867), log frequency ($F(3,116) < 1$), and isolation points ($F(3,116) = 2.26$, $p > .05$). Repetitions of syllables within the bisyllabic word stimuli (e.g., “line” in “hemline” and “dateline”) were approximately balanced across phonotactic condition. $\chi^2$ tests on the frequencies of repetitions as a function of condition revealed no significant differences among the conditions ($p = .98$).

*Nonwords.* The 240 monosyllabic nonwords were systemically combined to create two lists of 120 bisyllabic nonwords. All resulting stimuli contained the same vowel in the first and second syllables. The 240 nonwords were equally divided among the four probability/density conditions (high–high, high–low, low–high, and low–low) and split into two lists of 120 stimuli per list. The 120 nonwords appeared only once in each list. A complete list of the nonwords can be found in Appendix B. Phonotactic probabilities of the component syllables are given in Experiment 1. Stimulus durations were equivalent across phonotactic conditions (List 1, $F(3,116) = 1.75$, $p > .05$, and List 2, $F(3,116) = 1.20$, $p > .05$; high–high = 925; high–low = 903; low–high = 906; low–low = 961). All nonwords had isolation points at the third segment.

We created two lists of nonwords to counterbalance syllable order. List 1 consisted of nonwords with syllables in one order; stimuli in List

2 contained the same syllables in reverse order. This additional control of the nonword bisyllabic stimuli replicates the procedure used in Vitevitch et al. This method of syllable combination was not possible for the word stimuli.

All of the stimuli were spoken with stress on the first syllable in isolation by a trained phonetician and recorded. The stimuli were low-pass filtered at 4.8 kHz and digitized at a sampling rate of 10 kHz using a 12-bit analog-to-digital converter. All stimuli were edited into individual files and stored on computer disk. Correct stress placement by the speaker was confirmed by measuring the amplitude of the vowel of each syllable using a digital waveform editor.

### *Procedure*

Participants were tested individually. Each participant was seated in a booth equipped with a terminal and a pair of Telephonics TDH-39 headphones with an attached boom microphone that was positioned immediately in front of the participant's lips. The microphone was connected to a voice-key interfaced to a computer. The voice-key registered a response as soon as the participant began speaking. Presentation of stimuli and response collection was controlled by the computer.

A typical trial proceeded as follows: A prompt ("READY") appeared on the terminal. Participants were presented with one of the spoken stimuli at a comfortable listening level. Participants then repeated the item as quickly and as accurately as possible into the microphone. Reaction times were measured by the computer from the onset of the stimulus to the onset of the participant's verbal response. After registering a response, the computer began another trial. Participants were allowed a maximum of 3 s to respond before the computer automatically recorded a null response and presented the next trial.

All responses were recorded on audiotape for accuracy analysis. Accuracy was assessed by listening to the participants' responses and comparing them to a written transcription of the stimuli. A response was scored as correct if there was a match on all segments of the stimulus.

Twenty participants received one of two randomly ordered lists of 120 nonwords. Twenty additional participants received the list of 120 real word stimuli. Thus, lexicality of the stimuli was a between-participants manipulation. The words and nonwords were blocked in order to maximize the probability that participants would consistently process the stimuli at a sublexical or lexical level.

Prior to the experimental trials, each participant received 10 practice trials. These trials were used to familiarize the participants with the task and were not included in the final data analysis.

## *Results*

### *Words*

Mean reaction times and percent correct for each condition are shown in Fig. 6. Two (First-Syllable Probability/Density) × 2 (Second-Syllable Probability/Density) within-participants ANOVAs were performed. For the reaction times, neither the main effect of first-syllable probability/density nor second-syllable probability/density were significant (first syllable: $F_1(1,19) = 1.68$, $MSE = 631$, $p > .05$, and $F_2(1,116) < 1$, $MSE = 3424$; second syllable: both $F$s $< 1$). However, a significant interaction between first and second syllables was obtained ($F_1(1,19) = 12.25$, $MSE = 518$, and $F_2(1,116) = 3.86$, $MSE = 3424$).

Planned contrasts based on the interaction revealed that words in the high–high condition ($\bar{X} = 1084$) were responded to significantly more quickly than words in the high–low condition ($\bar{X} = 1103$; $F_1(1,19) = 12.15$, $F_2(1,116) = 4.17$), and words in the low–low condition ($\bar{X} = 1092$) were responded to significantly more quickly than words in the low–high condition ($\bar{X} = 1109$; $F_1(1,19) = 5.17$, $F_2(1,116) = 4.55$). Finally, there was no significant difference between the high–high and low–low conditions ($F_1(1,19) = 1.46$, $p = .24$, $F_2(1,116) = .16$, $p = .68$), nor between the high–low and low–high conditions ($F_1(1,19) = .65$, $p = .43$, $F_2(1,116) = .002$, $p = .96$). No significant effect of phonotactic probability was obtained for the percentage correct (all $F$s $< 1$).

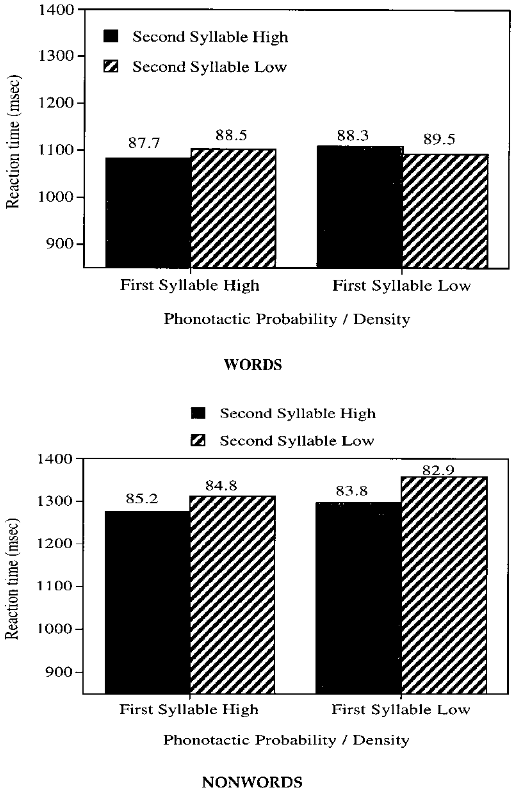


**FIG. 6.** Mean reaction times and percentages correct for the shadowing task in Experiment 4. Results for words are in the top panel and for nonwords in the bottom panel. First-syllable probability/density is plotted on the *x* axes. High second-syllable probability/density is indicated by solid bars and low second-syllable probability/density by striped bars. The mean percentage correct is shown above the bar for each condition.

### *Nonwords*

Nonwords with high probability/density first syllables ($\bar{X}$ = 1295) were repeated more quickly than those with low probability/density first syllables ($\bar{X}$ = 1328; $F_1(1,19) = 22.09$, *MSE* = 1011, and $F_2(1,116) = 4.53$, *MSE* = 7379). Nonwords with high probability/density second syllables ($\bar{X}$ = 1287) were repeated more quickly than those with low probability/density second syllables ($\bar{X}$ = 1335; $F_1(1,19) = 50.93$, *MSE* = 906, and $F_2(1,116) = 9.26$, *MSE* = 7379). The interaction between first and second syllables was not significant ($F_1(1,19) = 3.35$, *MSE* = 741, $p > .05$, and $F_2(1,116) < 1$, *MSE* = 7379). Overall, highly probable patterns were responded to more quickly than less probable patterns. No significant effect of phonotactic probability was obtained for the percentage correct (all *F*s < 1).

*Combined analyses.* Separate 2 (Lexicality) × 2 (First-Syllable Probability/Density) × 2 (Second-Syllable Probability/Density) ANOVAs were performed. Words ($\bar{X}$ = 1095) were repeated faster than nonwords ($\bar{X}$ = 1311; $F_1(1,38) = 11.13$, *MSE* = 72,631, $p < .01$, and $F_2(1,232) = 505.03$, *MSE* = 5401). Stimuli with high probability/density second syllables ($\bar{X}$ = 1192) were repeated faster than those with low probability/density second syllables ($\bar{X}$ = 1217; $F_1(1,38) = 22.65$, *MSE* = 630, and $F_2(1,232) = 7.07$, *MSE* = 5401).

The effect of probability/density on first syllables was larger for nonwords (33 ms) than for words (7 ms), resulting in a significant two-way interaction between first-syllable probability/density and lexicality ($F_1(1,38) = 30.38$, *MSE* = 821, $p < .001$, and $F_2(1,232) = 2.51$, *MSE* = 5401, $p = .11$). In addition, the overall effect of probability/density for second syllables was larger for nonwords (48 ms) than for words (2 ms), resulting in a significant two-way interaction between second-syllable probability/density and lexicality ($F_1(1,38) = 8.91$, *MSE* = 773, and $F_2(1,232) = 5.62$, *MSE* = 5401). Finally, a significant three-way interaction among first-syllable probability/density, second-syllable probability/density, and lexicality was obtained ($F_1(1,38) = 4.06$, *MSE* = 630, and $F_2(1,232) = 2.70$, *MSE* = 5401, $p = .10$). All of these interactions reflect the markedly different data patterns obtained for words and nonwords. No significant effects were obtained for the accuracy scores (all *F*s < 1).

### *Discussion*

The results of Experiment 4 demonstrate that bisyllabic nonwords composed of high probability segments and sequences are repeated faster than bisyllabic nonwords composed of low probability segments and sequences. These results replicate the findings of Vitevitch et al. (1997). For nonwords, phonotactic probability appears to have its effect as a sublexical level and operates in an additive manner across syllables.

In the case of bisyllabic real words, however, stimuli composed of two high probability syllables (high–high) or two low probability syllables (low–low) were shadowed more quickly. Stimuli consisting of syllables with different phonotactic probabilities (high–low and low–high) were responded to more slowly.

Before discussing the implications of these findings for the bisyllabic stimuli, two comments on methodological issues are in order. First, care must be taken in interpreting reaction times from shadowing experiments to ensure that the results are not artifacts of the production response. Two facts lead us to conclude that our results are not confounded: (1) Using a delayed naming task, Vitevitch et al. demonstrated that the reaction times to the nonwords used in the present experiment are *not* artifacts of the production response (see also Gaygen & Luce, 1998). (2) The results from Experiments 5 and 6 replicate the results for the word stimuli in tasks requiring button press responses.

The second methodological issue concerns the stimuli themselves. Because more stringent control could be exerted on the nonwords, we were able to match vowels both across probability/density conditions and within the nonwords themselves (i.e., both syllables of the nonwords contained the same vowel). Given the much smaller pool of word stimuli meeting the requirements of the present experiment, such control was not possible for the words. Also, the segmental compositions of the words and nonwords differ. (See Appendix B.) Two observations are in order regarding these differences: (1) As demonstrated in the posthoc analyses of Experiments 1–3, segment identity is not the sole source of the observed effects for these stimuli. (Recall that the bisyllabic stimuli were constructed from the monosyllables used in Experiment 1.) And (2), we are primarily interested in the changes in response patterns from monosyllabic to bisyllabic stimuli. Such direct comparisons are possible because the components of the bisyllabic stimuli were themselves the stimuli of interest in Experiments 1 through 3 (and in Vitevitch & Luce, 1998).

The results of the present experiment are consistent with the prediction for the words that a single dominant level across the two syllables—whether it be lexical or sublexical—would result in fastest reaction times, with mixed-syllable stimuli producing slowest processing times. These results provide further support for the hypothesis that *both* lexical and sublexical levels operate in the recognition of spoken stimuli—even for real words—and that each of these levels is marked by differential effects of phonotactic probability and density.

## EXPERIMENT 5

We now turn to a somewhat more detailed interrogation of lexical and sublexical processing. In particular, we examine recognition of our bisyllabic word and nonwords in the lexical decision task. In Experiment 3, we demonstrated that effects of probabilistic phonotactics for *nonwords* could be diminished—and effects of lexical competition induced—when participants were required to discriminate the nonwords from words. We argued that this reversal of the probability/density effect for nonwords resulted from the effects of lexical activation, causing nonword decisions to succumb to effects of lexical competition like those observed for the words in Experiment 1. We now attempt to ascertain the effects of induced lexical competition for bisyllabic nonwords in the lexical decision task.

We predict that effects of probabilistic phonotactics will again be attenuated or reversed for the longer nonwords. However, the adaptive resonance framework predicts that if no strong lexical resonances can be maintained throughout processing of the longer bisyllabic nonwords, sublexical effects should gain dominance later in the recognition process (i.e., for second syllables). More precisely, effects of lexical competition should be observed for nonwords only for *initial* syllables. Because no strong lexical resonance will develop over time for the nonword targets, sublexical processing should dominate later in the recognition process once the initial lexical discrimination phase has proven unsuccessful in providing evidence for the presence of a word. Note that we propose that sublexical chunks will always establish the strongest resonant states for the nonword stimuli. The predicted “lexical” effects for the initial syllable of the bisyllabic nonwords are expected to arise because of the relatively greater number of partially activated lexical chunks for high density initial syllables compared to low density initial syllables, which should slow the *nonword* response.

For the words, we again hypothesized effects emanating from both the lexical and sublexical levels, replicating the results obtained for words in Experiment 4. We hypothesize identical effects for words in naming and lexical decision for two reasons: First, we observed little difference between the magnitude of the density effects for monosyllabic words in the naming study reported in Vitevitch and Luce (1998) and those in the lexical decision study reported in Experiment 3 of the present investigation, suggesting that the degree of focus at the lexical level for words does not vary across these two particular tasks (although this is clearly *not* the case for the same–different task). Second, our account of the lexical decision task for words does not predict differential effects across the naming and lexical decision. In both tasks, we propose that responses are based on direct recognition of the target word: In both naming and lexical decision, input activates a set of lexical representations (i.e., neighborhood) in memory that are chosen among. Once a given representation reaches criterion for recognition, a response is initiated. Thus, whatever processes affect recognition in naming words should also be operative in recognizing a given item as a word and initiating a response in the lexical decision task. The situation for nonwords, however, is quite different: In the naming task, the nonword response can be generated by mapping segmental information onto motor codes in the absence of strong lexical activation from a given item (as demonstrated in Vitevitch & Luce, 1998). In lexical decision, however, the nonword must be compared against words in order to rule out the possibility that the stimulus is, in fact, a word. This comparison process necessarily involves assessment of lexical activity in the system, thus giving rise to effects of lexical competition for words. In short, we propose that responses to words in both naming and lexical decision are based on identical recognition processes, whereas responses to nonwords in the two tasks vary as a function of the nature of the required response.

## *Method*

### *Participants*

Thirty-five participants were recruited from the University at Buffalo community and were paid $5.

### *Materials*

Two lists of 480 stimuli were constructed for the lexical decision task. Each list contained 240 words and 240 nonwords. Half of the 240 words were the stimuli used in Experiment 4. The other half were filler items. Half of the 240 nonwords consisted of one of the lists of 120 nonword items used in Experiment 4. The other 120 nonword fillers were real words that had the last (or next to last) phoneme modified to make them nonwords. For example, the word "baseball" was modified to make "basebawp." These nonword fillers were included to maximize the probability that participants would listen to each stimulus in its entirety before making a response. See Experiment 4 for a complete description of the stimulus characteristics.

All stimuli were spoken in isolation and recorded by the same trained phonetician. The stimuli were low-pass filtered at 4.8 kHz and digitized at a sampling rate of 10 kHz using a 12-bit analog-to-digital converter. All words were edited into individual files and stored on computer disk.

### *Procedure*

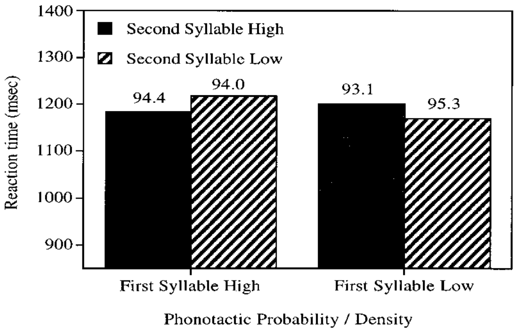
The procedure was the same as that in Experiment 3. Again, only responses made with the dominant hand were examined.

Each participant received one of two counterbalanced lists of 480 randomly ordered stimuli. Prior to the experimental trials each participant received 10 practice trials. These trials were used to familiarize the participants with the task and were not included in the final data analysis.

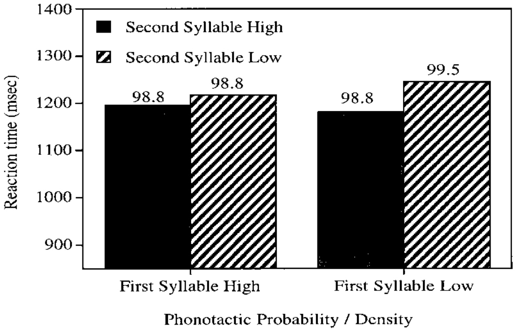
## *Results*

### *Words*

Mean reaction times and percentages correct for each condition are shown in Fig. 7. Two



WORDS



NONWORDS

**FIG. 7.** Mean reaction times and percentages correct for the lexical decision task in Experiment 5. Results for words are in the top panel and for nonwords in the bottom panel. First-syllable probability/density is plotted on the *x* axes. High second-syllable probability/density is indicated by solid bars and low second-syllable probability/density by striped bars. The mean percentage correct is shown above the bar for each condition.

(First-Syllable Probability/Density) × 2 (Second-Syllable Probability/Density) within-participants ANOVAs were performed. For the reaction times, no main effects of first-syllable probability/density ($F_1(1,14) = 2.40$, $MSE = 1474$, $p = .14$, and $F_2(1,116) < 1$) or second syllable probability/density (all *F*s < 1) were obtained. However, the interaction between first and second syllables was significant ($F_1(1,14) = 23.69$, $MSE = 654$, and $F_2(1,116) = 7.69$, $MSE = 8999$).

Planned contrasts based on this interaction revealed that words in the high–high condition ($\bar{X} = 1184$) were responded to significantly more quickly than words in the high–low condition ($\bar{X} = 1216$; $F_1(1,14) = 12.03$ and $F_2(1,116) = 4.31$), and words in the low–low condition ($\bar{X} = 1169$) were responded to significantly more quickly than words in the low–high condition ($\bar{X} = 1201$; $F_1(1,14) = 11.65$ and $F_2(1,116) = 4.69$). There was no significant difference between the high–high and low–low conditions ($F_1(1,14) = 2.62$, $p = .12$, and $F_2(1,116) < 1$), nor between the high–low and low–high conditions ($F_1(1,14) = 2.80$, $p = .11$, and $F_2(1,116) < 1$). No significant effects of phonotactic probability were obtained for accuracy (all *F*s < 1).

### *Nonwords*

For the reaction times, no difference between high ($\bar{X} = 1206$) and low ($\bar{X} = 1214$) probability/density conditions was found for the first syllable ($F_1(1,19) < 1$ and $F_2(1,116) < 1$). Nonwords with high probability/density second syllables ($\bar{X} = 1189$) were responded to more quickly than those with low probability/density second syllables ($\bar{X} = 1231$; $F_1(1,19) = 15.52$, $MSE = 2323$, and $F_2(1,116) = 4.56$, $MSE = 9562$). The interaction between first and second syllables was not significant ($F_1(1,19) = 3.40$, $p > .05$, and $F_2(1,116) = 1.48$, $p > .05$). No significant effects of phonotactic probability were obtained for accuracy (all *F*s < 1).

### *Combined Analyses*

Two (Lexicality) × 2 (First-Syllable Probability/Density) × 2 (Second-Syllable Probability/Density) ANOVAs were performed. High probability/density second syllables ($\bar{X} = 1191$) were responded to faster than low probability/density second syllables ($\bar{X} = 1212$). This effect was only significant by participants ($F_1(1,33) = 7.83$, $MSE = 1997$, and $F_2(1,232) = 1.77$, $MSE = 9281$, $p = .18$). There was an effect of probability/density for second syllables of the nonwords (42 ms) but not for the words (0 ms), resulting in an interaction between second syllable probability/density and lexicality that was significant by participants and marginal by items ($F_1(1,33) = 7.64$, $MSE = 1997$, $p < .01$, and $F_2(1,232) = 3.00$, $MSE = 9281$, $p = .08$). Finally, a significant interaction among first syllable probability/density, second syllable probability/density, and lexicality was obtained

($F_1(1,33) = 13.40$, $MSE = 1838$, and $F_2(1,232) = 7.87$, $MSE = 9281$).

Overall, words were responded to less accurately than the nonwords ($F_1(1,33) = 13.31$, $MSE = .001$, and $F_2(1,232) = 1526.18$, $MSE = .003$). We attribute the less accurate performance for the words to the presence of the foils with late isolation points, which may have induced a more conservative response criterion. That is, the presence of the foils may have biased participants to respond *nonword* more often than *word* in the presence of real word stimuli.

### *Discussion*

The results of Experiment 5 for the real words parallel those obtained in Experiment 4 using the shadowing task: High–high and low–low stimuli were responded to more quickly than high–low and low–high stimuli. As predicted, the results for the nonwords were somewhat different than those obtained in the shadowing task. In particular, we observed no significant effect of phonotactic probability for initial syllables in lexical decision. Furthermore, our data demonstrate that for longer nonwords, sublexical processes continue to dominate, even in lexical decision. This result is not particularly surprising given that we observed *sublexical* phonotactic effects for longer *words.*

The finding that the robust effects of probabilistic phonotactics observed for initial syllables of the nonwords in the shadowing task were severely attenuated in the present experiment points to the operation of the lexical discrimination process observed in Experiment 3 for monosyllabic nonwords. In the shadowing task, nonwords with high probability initial syllables were responded to 33 ms more quickly than nonwords with low probability initial syllables. In lexical decision, this difference was only 8 ms. This result is similar to our finding for monosyllabic nonwords, in which the effect of phonotactic probability observed in the shadowing task was reversed in the lexical decision task. (This is also similar to the attenuation of lexical processing in monosyllabic real words in Experiment 2.) Clearly, lexical discrimination processes dominated processing early on for the nonwords, mitigating effects of phonotactic probability for the initial syllables. That is, facilitatory effects of phonotactic probability for the initial syllables of the nonwords were compensated for by competitive effects among lexical representations. Apparently, because no single lexical representation was subsequently able to gain advantage in the recognition process, sublexical representations controlled processing for the later occurring information. In turn, these dominant sublexical representations resulted in facilitatory effects of phonotactic probability, hence producing no actual reversal of the effect of probability/density for the initial syllables of the nonwords. The differential effects of lexical processing revealed by comparisons of nonword response times in shadowing and lexical decision are not apparent for the words because these stimuli always strongly engage lexical activation.

## EXPERIMENT 6

Although a fairly clear picture now emerges as to the nature of the effects of phonotactics and lexical competition in the recognition of both short and long spoken words, we performed a final experiment in an attempt to place certain of these findings on a firmer empirical foundation. To this point, we have examined the processes of spoken word recognition using a number of fairly standard experimental paradigms. Each of these paradigms, however, encourages participants to base their responses on aspects of the form of the stimulus. By focusing attention on form-based representations, these tasks may exaggerate or distort the effects of phonotactics and neighborhood activation. For example, the auditory naming task may bias processing toward the sublexical level because a response may be made without accessing lexical representations. Similarly, the lexical decision task appears to bias processing toward the lexical level. Although these characteristics of the two tasks have proven useful in examining the relative effects of phonotactics and neighborhood activation, we performed a final experiment using a very different experimental methodology in order to better assess the role of the two levels of representation in the on-line processing of spoken words.

We employed a semantic categorization task similar to that used by Forster and Shen (1996). In this task, participants hear a word over headphones and must decide as quickly and as accurately as possible whether the word corresponds to an *animate* or *inanimate* object. We hypothesized that the processes enlisted to retrieve the semantic information required to make a response in this task would not unnaturally bias either the sublexical of the lexical level. Our hope, therefore, was to replicate a portion of our findings using a method that does not require strict attention to the form of the spoken stimulus.

Because of the nature of the semantic categorization task, we were only able to use real word stimuli. Given the somewhat nonintuitive results of Experiments 4 and 5, we chose our bisyllabic word stimuli for this experiment. Also because of the nature of the task, we were forced to select a subset of the stimulus words used in the previous two experiments because only certain of our original stimuli could be easily classified on the animacy dimension. Thus, the present experiment provides a strong further test of our hypotheses regarding the results from Experiments 4 and 5 by using only a subset of the original stimuli in a markedly different task.

## *Method*

### *Participants*

Thirty-two participants were recruited from the Indiana University Introductory Psychology pool and received partial credit for a course requirement.

### *Materials*

Eighty bisyllabic words from the 120 bisyllabic word stimuli used in Experiments 4 and 5 that could be clearly categorized as inanimate were selected. (There were too few animate words in the original list to include.) These 80 bisyllabic words fell into one of the four probability/density conditions (high–high, high–low, low–high, low–low) with 20 words in each condition. An additional eighty bisyllabic words that described various "animate" creatures (of either real or mythical origin) were then selected from various dictionaries and encyclopedias. (A complete listing of the "animate" and "inanimate" words is in Appendix C.)

All stimuli used in this experiment were spoken in isolation and recorded by the first author. The stimuli were filtered at 10.4 kHz and digitized at a sampling rate of 20 kHz using a 16-bit analog-to-digital converter. All words were edited into individual files and stored on computer disk.

The following variables were equated for the word stimuli across the four conditions: stimulus duration ($F(3,76) < 1$), log frequency ($F(3,76) < 1$), and isolation points ($F(3,76) < 1$). Average segment and biphone probabilities were .1979 and .0188 for the high probability/density component syllables and .1258 and .0117 for the low probability/density component syllables. The mean log-frequency-weighted neighborhood density was 49 for the high syllables and 36 for the low syllables.

### *Procedure*

Participants were tested in groups no larger than three. Each participant was seated in a booth equipped with a pair of Beyerdynamic DT-100 headphones and a response box. The lefthand button on the response box was labeled *animate* and the righthand button on the response box was labeled *inanimate.* Presentation of stimuli and response collection was controlled by computer.

A trial proceeded as follows: A light at the top of the response box was illuminated to indicate the beginning of a trial. Participants were then presented with one of the spoken stimuli at a comfortable listening level. Reaction times were measured from the onset of the stimulus to the button press response. If the maximum reaction time (3 s) expired, the computer automatically recorded an incorrect response and presented the next trial. Participants were instructed to respond as quickly and as accurately as possible.

Prior to the experimental trials, each participant received 10 practice trials. These trials were used to familiarize the participants with the task and were not included in the final data analysis.

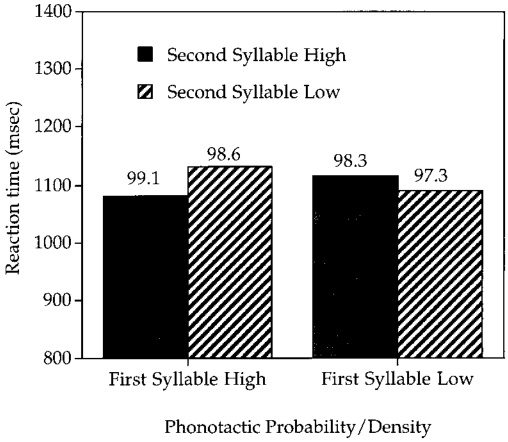


**FIG. 8.** Mean reaction times and percentages correct for the semantic decision task in Experiment 6. First-sylable probability/density is plotted on the *x* axes. High second-syllable probability/density is indicated by solid bars and low second-syllable probability/density by striped bars. The mean percentage correct is shown above the bar for each condition.

### *Results*

Mean reaction times and percentages correct for each condition are shown in Fig. 8. Two (First-Syllable Probability/Density) × 2 (Second-Syllable Probability/Density) within-participants ANOVAs were performed. For the reaction times, no main effects of first-syllable probability/density (both *F*s $< 1$) or second syllable probability/density (both *F*s $< 1$) were obtained. However, the interaction between first and second syllables was significant ($F_1(1,31) = 17.41$, $MSE = 2745$, and $F_2(1,76) = 8.77$, $MSE = 7111$).

Planned contrasts based on this interaction revealed that words in the high–high condition ($\bar{X} = 1080$) were responded to significantly more quickly than words in the high–low condition ($\bar{X} = 1131$; $F_1(1,31) = 14.78$ and $F_2(1,76) = 4.65$), and words in the low–low condition ($\bar{X} = 1089$) were responded to significantly more quickly than words in the low–high condition ($\bar{X} = 1116$; $F_1(1,31) = 4.23$ and $F_2(1,76) = 4.14$). There was no significant difference between the high–high and low–low conditions (both *F*s $< 1$), nor between the high–low and low–high conditions ($F_1(1,31) = 1.37$ and $F_2(1,76) < 1$). No significant effects of phonotactic probability were obtained for accuracy (both *F*s $< 1$).

### *Discussion*

The results of Experiment 6 replicate the results for the word stimuli from Experiments 4 and 5, further suggesting that two levels of representation and process operate in spoken word recognition. To make a judgment based on semantic information ("animate" vs. "inanimate"), participants must access the word from the lexicon. The processes involved in making this decision followed the same pattern found in the naming and lexical decision tasks. Specifically, stimuli composed of two high probability syllables or two low probability syllables were responded to more quickly than stimuli consisting of syllables with mixed probability/density (high–low and low–high). The data from Experiment 6 suggest that the results of the shadowing (Experiment 4) and lexical decision (Experiment 5) tasks were not due to task specific effects.

## GENERAL DISCUSSION

We began this investigation with an apparent contradiction: Spoken stimuli that consist of high probability phonotactic patterns are processed more quickly and accurately than those consisting of low probability patterns. However, stimuli residing in low density similarity neighborhoods are processed more quickly and accurately than those in high density neighborhoods. The contradiction lies in the strong correlation between probabilistic phonotactics and neighborhood density: Residence in a densely populated neighborhood virtually assures high phonotactic probability. Likewise, low phonotactic probability means fewer neighbors.

A clue to the solution of this puzzle lay in the discovery that the lexical status of the spoken stimulus determines the effects of phonotactic probability and neighborhood density. Nonwords appear to show facilitatory effects of phonotactics, whereas words succumb to competition among lexical neighbors. Based on this finding, Vitevitch and Luce (1998) proposed a simple account: When processing is dominated by a sublexical level—as for nonwords—effects of probabilistic phonotactics are observed.

However, when lexical representations dominate processing—as for words—effects of lexical competition emerge.

We amplified this simple two-level account by proposing a framework based on Grossberg et al.'s adaptive resonance model of speech perception. In their model, resonant states established between list chunks in short-term memory and items in working memory constitute speech percepts. Four features of this model are important: (1) List chunks may correspond to units of various sizes (such as segments, sequences of segments, and words), (2) all things being equal, the largest and most predictive list chunk will dominate processing, in part by inhibiting smaller chunks, (3) activation of list chunks is a function of their frequencies (or probabilities) of occurrence, and (4) similar list chunks compete with one another via lateral inhibitory links.

### *Sublexical and Lexical Levels in Spoken Word Recognition*

The postulation of separate lexical and sublexical levels of processing has deep implications for how models of spoken word recognition account for effects of probabilistic phonotactics. Although the TRACE model has explicit, tiered levels of representation, it nonetheless proposes that phonotactic effects emanate from lexical items themselves. Models such as Shortlist, on the other hand, argue for lexical independence of at least some phonotactic effects. Recent work by Pitt and McQueen (1998; see also Gaygen, 1998) strongly suggests that phonotactic effects may be observed when no obvious lexical involvement is possible. Indeed, these researchers demonstrate that effects thought previously to support the TRACE model's lexical account of phonotactics are in fact sublexical. Our results are consistent with Pitt and McQueen's argument for the sublexical locus of phonotactic effects. In particular, our data demonstrating that sublexical phonotactic effects manifest themselves when effects of lexical competition are minimized lends support to Pitt and McQueen's assertion.

Further support for the sublexical locus of phonotactic effects comes from a recent study by Mattys, Jusczyk, Luce, and Morgan (1998) examining 9-month-olds' sensitivity to within- and between-word phonotactic probabilities. They demonstrated that infants preferred between-word probabilistic sequences when prosodic and pause information were consistent with a two-word utterance and within-word sequences when this information was consistent with one-word sequences. It is highly unlikely, especially for infants, that the differential sensitivity to within- and between-word phonotactic probabilities is lexically based. Instead, it appears that infants as young as 9 months have encoded probabilistic phonotactic information that is *not* contained within words in their lexicons.

Also related to the hypothesis that both lexical and sublexical units may be involved in the processing of spoken stimuli (under appropriate circumstances) is the problem of lexical interactions with sublexical processing (see Norris et al., 1998; Samuel, 1996): Do lexical units directly affect processing of sublexical units or is processing carried out autonomously at each level of analysis, with the products of the analyses combined at later stages of decision making? The adaptive resonance framework adopted here does not neatly fit into either the autonomous or interactive camps. On the one hand, sublexical list chunks *cannot* be directly facilitated by lexical chunks. Lexical chunks may mask or inhibit overlapping sublexical chunks, but that is the extent of their direct interaction. From one perspective, then, the adaptive resonance framework is an autonomous model. On the other hand, complex interactions may arise via the resonance loops established between list chunks and items in working memory. For example, lexical list chunks may affect items, which in turn may affect sublexical chunks. The outcome of such interactions, however, may be quite complex and depend on the dynamics of processing in the chunking network, the nature of the input, attentional focus, and so on. The fundamental problem in categorizing the adaptive resonance model along the dimension "autonomous-interactive" is that the model does not incorporate traditional notions of tiered sublexical and lexical levels and thus does not fall easily on either side of the current debate. (For an excellent analysis of this issue from the "autonomous" perspective, see Norris et al., 1998.)

Before leaving the issue of interactive lexical and sublexical effects, one recent study of the effects of neighborhood activation on segmental perception is worthy of mention. Newman, Sawusch, and Luce (1997) presented subjects with nonwords that varied on frequency-weighted neighborhood structure. In certain conditions of their experiment, the initial segments of the nonsense words were digitally edited to make their identity ambiguous. In these cases, Newman et al. found that subjects were more likely to label ambiguous segments as belonging to nonsense words in dense, high frequency neighborhoods than to nonsense words occurring in sparse, low frequency neighborhoods. Newman et al.'s finding appears to be indicative of a phonotactic effect, in that dense neighborhoods resulted in more activation at the segmental level. However, subsequent analyses have shown that simple segmental or lower order phonotactic probabilities do not account for their results (Newman, Sawusch, & Luce, 1998). One interpretation of the Newman et al. findings that is consistent with our adaptive resonance framework is that the nonwords in their study partially activated lexical chunks. Because of increased lateral inhibition among lexical chunks corresponding to nonwords in dense neighborhoods, masking of the sublexical chunks on which the responses in this task are based would have been less than masking from lexical chunks activated by nonwords in sparse neighborhoods. The sublexical chunks driving the response would have higher resonant states if the nonword occurred in a dense neighborhood, compared to nonwords in sparse neighborhoods. Thus, it is possible that the source of the effect observed by Newman et al. lay in the interaction of lexical and sublexical chunks.

### *Other Models of Spoken Word Recognition*

Although we have chosen to base our interpretations of the combined effects of probabilistic phonotactics and neighborhood activation on the adaptive resonance model, our results are broadly consistent with other models of spoken word recognition that posit both lexical and sublexical levels of processing, such as TRACE and Shortlist. In addition, our results provide further support for the now widespread assumption in many models (e.g., TRACE, Shortlist, NAM) that lexical representations compete—in one way or another—in the recognition process. Clearly, models that fail to incorporate mechanisms of lexical competition, such as the Cohort Model (Marslen-Wilson & Tyler, 1980), or models that fail to specify a sublexical level of representation at which effects of phonotactics may operate, such as NAM, are inadequate (although a version of NAM, dubbed PARSYN, has recently been proposed that incorporates a segmental level of representation; see Auer & Luce, 1998, and Luce, Goldinger, Auer, & Vitevitch, 1998).

Nevertheless, among current models of spoken word recognition, only Shortlist appears to embody the requisite architecture for accounting for the *opposite* effects of probability and density as a function of lexicality. Shortlist's recurrent network enables it to learn about sequential dependencies among segments independent of lexical units themselves (see Elman, 1990). Moreover, Shortlist predicts that processing is dependent on the level (sublexical vs. lexical) to which participants attend. In the case of nonwords—where " . . . lexical effects are at their weakest . . . " (Norris, 1994, p. 210)—phonotactic effects will arise as participants attend to the phonemic level of representation, possibly resulting in high probability/density nonwords being responded to faster than low probability/density nonwords. In the case of real words, participants may attend primarily to the lexical level, possibly resulting in low probability/density words being responded to faster than high probability/density words. However, whether Shortlist is capable of producing the results for the longer stimuli observed in the present study is at present unclear.

### *Implications for Phonological Memory*

Finally, our results demonstrating differential effects of probabilistic phonotactics and neighborhood activation for short and long spoken words may have implications for Baddeley and Gathercole's work on the phonological loop (see Baddeley, Gathercole, & Papagno, 1998). Gathercole (1995) and Gathercole, Willis, Emslie, and Baddeley (1991) have demonstrated that children are more accurate at repeating short nonwords than long nonwords, suggesting that nonword repetition in children is affected by the capacity of verbal short-term memory. Baddeley, Thomson, and Buchanan (1975) have also demonstrated decreased capacity of the phonological loop for longer words in adults (the *word length effect*). Long stimuli may place greater demands on verbal short-term memory, thus increasing the potential role of phonological memory in recognition. Factors affecting maintenance of items in short-term memory—such as neighborhood density and probabilistic phonotactics—may thus take on important functions in the recognition process when short-term memory is taxed by longer stimuli. For example, effects of sublexical phonotactics that are not apparent for shorter words (Experiments 1–3) appear to take on increased importance when phonological short-term memory is stressed in the processing of bisyllabic words (Experiments 4–6).

Gathercole (1995) and Gathercole, Willis, Emslie, and Baddeley (1991) have also demonstrated that the degree to which nonwords sound like real words (i.e., their phonotactic probability) affects children's repetition accuracy. According to Baddeley et al., this finding demonstrates that phonological knowledge in long-term memory may attenuate the role of the phonological loop when phonotactic probabilities are high. Although our data provide no direct evidence that high probability phonotactic patterns reduce demands on the phonological loop, they clearly implicate a role for probabilistic phonotactics in the processing of longer, bisyllabic words. Although Baddeley et al. are reluctant to claim a role for the phonological loop in normal adult spoken word recognition, we believe our results demonstrate that longer spoken words may indeed place some demands on short-term memory, as evidenced by the differential effects of probability/density observed for syllables in isolation (Experiments 1–3) compared to the same syllables in bisyllabic stimuli (Experiments 4–6). More specifically, the longer time window required for establishing a dominant resonant state for longer spoken stimuli may in some way increase demands on memory storage (see, however, Grossberg & Stone, 1986, for a discussion of capacity limitations).

Our framework for the on-line processing of spoken words also bears some resemblance to Gathercole et al.'s (1991) account of vocabulary acquisition by children. They too suggest that there may be two levels of representation, one analogous to the sublexical level and the other the lexical level. According to Gathercole et al., the "sublexical level" is affected by the same factors that may affect short-term phonological memory, such as the strength of links between sequential phonological elements and the decay rate of the phonological representation. Gathercole et al. also propose that similar items may be activated in long-term memory (i.e., the lexicon) to form an abstract phonological frame. This frame may then act as a mnemonic device for novel items, aiding in the later retrieval. Not only may two levels of representation be used to *acquire* novel lexical items, as suggested by Gathercole et al., but these two levels of representation may also be used in the on-line processing of spoken words, as the current findings suggest.

## CONCLUSION

Our results suggest that probabilistic phonotactic information is not only represented in memory but that it, together with information regarding phonological similarity neighborhoods, affects the time course of spoken word recognition. The results of a series of experiments using several different tasks and types of stimuli are accounted for by an adaptive resonance framework for spoken word recognition that embodies two levels of representation—a lexical level and a sublexical level. The hypothesis of two levels of representation with dissociable and distinct effects on processing reveals, in part, the complexity of the recognition process: Predicting processing of spoken words involves simultaneous consideration of the nature of the task used to interrogate the recognition process, the level of representation that dominates the response (Cutler & Norris, 1979; Foss & Blank, 1980), and the probabilistic phonotactics and similarity neighborhood structure of the spoken stimulus.

# APPENDIX A

## High Probability Words

back
bar
bat
bell
boat
cake
calm
cap
car
case
cat
coal
coat
cob
come
con
cot
cup
cut
dead
deer
down
fan
fare
for
hair
head
hill
kick
kin
line
mad
man
mar
mass

mat
mate
mean
mole
muss
nick
pad
pan
pass
path
pen
pick
piece
pin
pipe
pit
pot
ram
ran
red
rein
rock
run
sack
sale
sauce
set
sick
side
size
soar
suit
sun
well
year

## Low Probability Words

bag
ball
base
bomb
book
boom
boot
bull
check
date
dish
dog
dumb
face
fall
feed
fight
fish
home
hook
hop
hot
house
jack
jam
knife
leg
life
light
load
lock
log
long
luck
made

mouth
name
nap
net
night
nut
page
peep
pull
rag
rail
road
room
shine
ship
shot
tail
tape
team
tide
time
top
touch
town
tug
walk
wall
war
wash
web
weight
wife
wood
work
worm

## High Probability Nonwords

fʌ1
ʧʌn
mʌb
sʌʃ
tʌ1
sʌʤ
hʌs
ʤʌn
dʌs
sʌz
sʌg
kʌk
sʌv
ɹʌ1
sʌd
1ʌn

ɹaɪɹ
maɪd
haɪs
saɪb
vaɪt
ʤaɪn
saɪv
ʧaɪn
saɪp
saɪm
gaɪn
paɪt
saɪs
daɪt
saɪk
saɪ1

bis
siv
dik
nin
hin
bil
dis
dit
fin
ɹit
ɹis
ɹin
vet
ɹeb
meb
keb

ked
sed
nen
ten
pek
ses
dɝs
mɝn
sɝz
fɝt
tɝt
sɝg
pɝv

## Low Probability Nonwords

ðʌʃ
ðʌʤ
jʌʃ
ðʌʧ
ɵʌʃ
jʌʤ
ʧʌʃ
ɵʌʤ
jʌʧ
ʧʌʤ
ɵʌʧ
ʃʌʤ
wʌʃ
ʧʌʧ
ʃʌʧ
ðʌz

ðaɪb
ʤaɪz
ðaɪv
ʃaɪb
ʧaɪz
waɪð
ðaɪm
naɪð
kaɪð
ðaɪp
ʃaɪv
ʧaɪb
ʃaɪm
ʃaɪp
gaɪb
ʤaɪm

ðitʃ
jiʤ
ziʤ
jiʧ
ziʧ
ʧiʃ
ʧið
giʤ
ðig
giʧ
jig
zig
ɵeʒ
ɵeð
ɵeɵ
ɵeg

ɵez
ʧeʤ
veʒ
ʃeʤ
veð
geʒ
jɝz
jɝɵ
ʃɝɵ
jɝg
ʃɝz
ʧɝɵ
ʧɝz

## APPENDIX A—*Continued*

| High Probability Nonwords | | | | Low Probability Nonwords | | | |
|---|---|---|---|---|---|---|---|
| pʌm | baɪn | seb | vɝn | wʌʤ | ʤaɪp | ʤeʒ | ʃɝg |
| bʌ1 | haɪn | mep | pɝb | ðʌg | faɪð | ʤeð | jɝʧ |
| pʌ1 | kis | ges | mɝs | ðʌv | ðiʃ | ʧeʒ | ʧɝg |
| sʌt | ʧin | wes | kɝm | jʌz | ðið | ʧeð | nɝθ |
| mʌn | kik | hes | sɝp | wʌʧ | jiʃ | ʤeθ | nɝz |
| sʌs | ɹig | sep | pɝd | ðʌd | giʃ | ʃeʒ | ʃɝʧ |
| sʌ1 | sig | peb | fɝs | θʌz | ziʃ | θeʤ | 1ɝθ |
| kʌn | θin | ɹem | bɝs | ʧʌz | jið | ʃeð | ʃɝʤ |
| taɪs | fik | nes | kɝn | ðaɪð | zið | ʧeθ | θɝθ |
| daɪp | kit | tes | sɝd | ʃaɪð | gið | ʃeθ | 1ɝz |
| vaɪɹ | pim | pep | sɝ1 | ʤaɪð | ðiθ | ʤeg | jɝp |
| vaɪk | fis | 1e1 | sɝm | ʧaɪð | jiθ | ʧeg | ʧɝʤ |
| baɪs | vin | hen | sɝk | gaɪð | ziθ | ʃeg | nɝg |
| faɪk | ɹiz | pem | pɝn | ðaɪz | giθ | ʤeʤ | gɝg |
| | | | sɝt | | | | ʤɝθ |
| | | | sɝn | | | | θɝz |
| | | | sɝs | | | | jɝv |

## APPENDIX B: BISYLLABIC WORDS

| High–High | High–Low | Low–High | Low–Low |
|---|---|---|---|
| madcap | cattail | hemline | dishrag |
| carfare | ramrod | timepiece | hemlock |
| reindeer | barroom | warfare | logjam |
| molehill | catwalk | dateline | boomtown |
| fanfare | sundial | feedback | bootleg |
| capsize | backwash | pipeline | yuletide |
| forehead | deadweight | bombshell | ragtime |
| pancake | penknife | wholesale | fishhook |
| manhole | bellhop | housecoat | shellfish |
| cutback | passbook | pulpit | wedlock |
| markup | contour | peephole | jackknife |
| ransack | kinship | topcoat | tapeworm |
| combat | yearlong | charcoal | hotshot |
| comeback | carload | houseboat | lifelong |
| kickback | madhouse | knapsack | network |
| mascot | potluck | nightcap | ballroom |
| pinhole | rampage | shamrock | baseball |
| sensor | deadlock | tugboat | boathouse |
| setback | pitfall | bobcat | bullfight |
| barbell | redwood | checkmate | chestnut |
| backside | catfish | dumbbell | doghouse |
| cupcake | cobweb | facedown | homemade |
| deadline | meantime | homesick | homeroom |
| format | mustang | lifeboat | housewife |
| hairline | nickname | mouthpiece | housework |
| picnic | padlock | roommate | matchbook |
| rundown | pastime | bagpipe | nighttime |

## APPENDIX B—*Continued*

| High–High | High–Low | Low–High | Low–Low |
|---|---|---|---|
| saucepan | sunfish | teammate | railroad |
| suitcase | sunlight | touchdown | walnut |
| welfare | sunshine | warpath | wartime |

### BISYLLABIC NONWORDS

| High–High | High–Low | Low–High | Low–Low |
|---|---|---|---|
| fʌ1ʧʌn | sʌvwʌʃ | ðʌvpʌ1 | ðʌʃʃʌʤ |
| mʌbsʌʃ | ɹʌ1ʧʌʧ | jʌzsʌt | jʌʃðʌʧ |
| tʌ1sʌʤ | sʌdʃʌʧ | wʌʧmʌn | ɵʌʃjʌʤ |
| hʌsʤʌn | 1ʌnðʌz | ðʌdsʌs | ʧʌʃɵʌʤ |
| dʌssʌz | pʌmwʌʤ | ɵʌzsʌ1 | jʌʧʧʌʤ |
| sʌgkʌk | bʌ1ðʌg | ʧʌzkʌn | ɵʌʧʃʌʤ |
| taɪsdaɪp | saɪvðaɪm | ʃaɪmsaɪs | ðaɪðʃaɪð |
| vaɪɹvaɪk | ʧaɪnnaɪð | ʃaɪpdaɪt | ʤaɪðʧaɪð |
| baɪsfaɪk | saɪpkaɪð | gaɪbsaɪk | gaɪððaɪz |
| ɹaɪɹmaɪd | saɪmðaɪp | ʤaɪmsaɪ1 | ðaɪbʤaɪz |
| haɪssaɪb | gaɪnʃaɪv | ʤaɪpbaɪn | ðaɪvʃaɪb |
| vaɪtʤaɪn | paɪtʧaɪb | faɪðhaɪn | ʧaɪzwaɪð |
| kisʧin | bisðiʧ | ʧiðdis | ðiʃðið |
| kikɹig | sivjiʤ | giʤdit | jiʃgiʃ |
| sigɵin | dikziʤ | ðigfin | ziʃjið |
| fikkit | ninjiʧ | giʧɹit | ziðgið |
| pimfis | hinziʧ | jigɹis | ðiɵjiɵ |
| vinɹiz | bi1ʧiʃ | zigɹin | ziɵgiɵ |
| vetɹeb | nesʧeɵ | ɵezked | ɵeʒɵeð |
| mebkeb | tesʃeɵ | ʧeʤsed | ɵeɵɵeg |
| sebmep | pepʤeg | veʒnen | ʤeʒʤeð |
| geswes | 1e1ʧeg | ʃeʤten | ʧeʒʧeð |
| hessep | henʃeg | veðpek | ʤeɵʃeʒ |
| pebɹem | pemʤeʤ | geʒses | ɵeʤʃeð |
| dɝsmɝn | pɝdʃɝʧ | ʧɝʤsɝm | jɝzjɝɵ |
| sɝzfɝt | fɝs1ɝɵ | nɝgsɝk | ʃɝɵjɝg |
| tɝtsɝg | bɝsʃɝʤ | gɝgpɝn | ʃɝzʧɝɵ |
| pɝvvɝn | kɝnɵɝɵ | ʤɝɵsɝt | ʧɝzʃɝg |
| pɝbmɝs | sɝd1ɝz | ɵɝzsɝn | jɝʧʧɝg |
| kɝmsɝp | sɝ1jɝp | jɝvsɝs | nɝɵnɝz |

## APPENDIX C BISYLLABIC INANIMATE WORDS VARYING IN PHONOTACTIC PROBABILITY

| High–High | High–Low | Low–High | Low–Low |
|---|---|---|---|
| madcap | ramrod | hemline | dishrag |
| carfare | barroom | timepiece | hemlock |
| fanfare | sundial | dateline | logjam |
| capsize | backwash | feedback | boomtown |
| pancake | deadweight | pipeline | bootleg |
| cutback | penknife | bombshell | ragtime |
| markup | passbook | wholesale | wedlock |
| ransack | contour | peephole | jackknife |
| comeback | kinship | topcoat | hotshot |

## APPENDIX C—*Continued*

| High–High | High–Low | Low–High | Low–Low |
|---|---|---|---|
| kickback | yearlong | charcoal | lifelong |
| pinhole | carload | houseboat | network |
| setback | madhouse | knapsack | ballroom |
| barbell | potluck | nightcap | baseball |
| cupcake | rampage | tugboat | boathouse |
| format | deadlock | checkmate | homeroom |
| picnic | pitfall | homesick | housework |
| rundown | meantime | mouthpiece | matchbook |
| saucepan | nickname | bagpipe | nighttime |
| suitcase | padlock | touchdown | railroad |
| welfare | pastime | warpath | wartime |

BISYLLABIC ANIMATE WORDS

aardvark
baboon
badger
beaver
beetle
bison
bobcat
bulldog
bullfrog
buzzard
camel
catfish
cattle
cheetah
chicken
cockroach
condor
cougar
cricket
cuckoo
dolphin
donkey
dragon
eagle
emu
falcon
ferret
giraffe
greyhound
groundhog
hamster
hedgehog
hornet
jaguar
jellyfish
junebug
leopard
lion
lizard
llama
lobster
magpie
mantis
mayfly
mongoose
monkey
ostrich
otter
panda
parrot
partridge
penguin
pheasant
pigeon
pony
porpoise
python
rabbit
raccoon
raven
reindeer
seahorse
seaslug
shellfish
squirrel
stallion
stingray
sunfish
swordfish
tadpole
termite
tiger
tortoise
toucan
turkey
turtle
walrus
warthog
weasel
zebra

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