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Phonotactics, density, and entropy in spoken word recognition

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Previous research has demonstrated that increases in phonotactic probability facilitate spoken word processing, whereas increased competition among lexical representations is often associated with slower and less accurate recognition. We examined the combined effects of probabilistic phonotactics and lexical competition by generating words and nonwords that varied *orthogonally* on phonotactics and similarity neighbourhood density. The results from a speeded same-different task revealed simultaneous *facilitative* effects of phonotactics and *inhibitory* effects of lexical competition for real word stimuli. However, the nonword stimuli produced an apparently anomalous pattern of results. In a subsequent experiment, we identified the source of this anomaly by estimating behaviourally the specific lexical competitors activated by our nonwords. Our results suggest that, under specific circumstances, neighbourhood density and probabilistic phonotactics may combine to produce non-additive or synergistic effects of lexical competition on processing times.

Increased frequency of the components of spoken stimuli facilitates processing (Pitt & Samuel, 1995; Vitevitch & Luce, 1999). At the same time, competition among lexical representations inhibits processing (Luce, Goldinger, Auer, & Vitevitch, 2000; Luce & Pisoni, 1998; Vitevitch & Luce, 1999). Both of these effects are predicted by any of a class of activation-competition models, including Shortlist (Norris, 1994), TRACE (McClelland & Elman, 1986), PARSYN (Luce et al., 2000), and

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ARTPHONE (Grossberg, Boardman, & Cohen, 1997). In particular, each of these models predicts that sublexical frequency effects—or effects of *probabilistic phonotactics*—are as much a part of the recognition process as the well-documented effects of lexical competition.

Empirical support for the distinction between sublexical and lexical effects in spoken word recognition comes, in part, from a number of studies conducted by Vitevitch and Luce (1998, 1999; see also Pitt & Samuel, 1995), who investigated processing of words and nonwords that varied in probabilistic phonotactics (defined as the positional frequencies of segments and biphones) and neighbourhood density (a measure of lexical competition; see Luce & Pisoni, 1998). Specifically, they examined stimuli falling into one of four conditions: (1) High density-high phonotactic probability words, (2) low density-low phonotactic probability words, (3) high density-high phonotactic probability nonwords, and (4) low density-low phonotactic probability nonwords. Note that for both the words and nonwords, neighbourhood density and probabilistic phonotactics *covaried*, reflecting the strong positive correlation in the language between number of overlapping words and segmental frequency. Typically, as the number of overlapping words increases, the frequencies of the segments comprising the overlapping words also increase.

When *words* were presented in auditory naming and same-different matching tasks, *inhibitory* effects of neighbourhood density were observed: High probability-density words were responded to more slowly than low probability-density words. However, for *nonwords*, a *facilitative* effect of probabilistic phonotactics was obtained: High probability-density nonwords were responded to more quickly than low probability-density nonwords. These results are consistent with the hypothesis that effects of similarity neighbourhood density are inhibitory and have a lexical focus whereas effects of probabilistic phonotactics are facilitative and have a sublexical focus.

To garner further evidence for the operation of two levels of representation and processing, Vitevitch and Luce attempted to (1) bias the processing of nonwords toward the lexical level and (2) bias the processing of words toward the sublexical level. If effects of similarity neighbourhood density and probabilistic phonotactics have loci at different levels of processing, encouraging processing of nonwords at a lexical level should reveal effects of neighbourhood competition. To this end, Vitevitch and Luce (1999) presented words and nonwords that varied on phonotactic probability and density in an auditory lexical decision task. This task necessitates activation of lexical items in memory to categorise the stimulus successfully, even when the stimulus is a nonword. That is, to make a lexical decision on both words and (phonotactically legal) nonwords, one must activate representations at a lexical level. Thus, Vitevitch and Luce predicted that the same nonwords that previously showed facilitative effects of probabilistic phonotactics in the naming and same-different tasks would show neighbourhood density effects in auditory lexical decision. Their predictions were confirmed: Words and nonwords with high probability phonotactics and neighbourhood density were responded to more slowly than words and nonwords with low probability phonotactics and neighbourhood density.

Vitevitch and Luce (1999) also attempted to determine if the effects of neighbourhood density that are so pervasive for words could be modified by focusing participants' processing on a sublexical level. They again presented words and nonwords that covaried on phonotactic probability and neighborhood density in a same-different task. In the previous experiment using this task, Vitevitch and Luce presented the words and nonwords blocked. That is, participants heard a list containing only words or a list containing only nonwords. They reasoned that if the presentation of words and nonwords was mixed, participants would focus their processing on the sublexical level, which is common to *all* of the stimuli. Although they did not predict that words would actually show a reversal of the density effect in favour of probabilistic phonotactics (owing to the overwhelming dominance of the lexical level in normal spoken language processing), they nonetheless predicted an attenuation of the effect of similarity neighbourhood competition. Again, the predictions were confirmed: High phonotactic probability nonwords were responded to faster than low phonotactic probability nonwords. However, the effects of similarity neighbourhood competition previously observed for these word stimuli were now considerably attenuated, resulting in no significant effect of neighborhood density for the words.

Despite the previous demonstrations of differential effects of lexical competition and sublexical frequency, to date there has been no definitive demonstration of *simultaneous* inhibitory effects of lexical competition and facilitative effects of probabilistic phonotactics for real words. Given the crucial role phonotactics may play in distinguishing between autonomous and interactive models (Norris, McQueen, & Cutler, 2000), an important step in determining the loci of effects of sublexical phonotactics and lexical competition is to demonstrate their combined effects on real word processing within a given task environment. In our own previous work (Vitevitch & Luce, 1999), we speculated that unpacking the two effects by orthogonally combining neighbourhood density and probabilistic phonotactics might be impossible, given the high correlation between the two variables. This speculation proved to be unfounded.

We examined the combined effects of lexicality, similarity neighbourhood density, and probabilistic phonotactics on processing times for carefully matched sets of spoken words and nonwords. In the course of our investigation, we not only confirmed and extended previous findings, we uncovered an effect that can not be predicted by a *simple* combination of activation and competition at sublexical and lexical levels of representation.

EXPERIMENT 1

Method

Participants. Forty-five English-speaking adult participants were recruited from the University at Buffalo community. All participants reported no history of a speech or hearing disorder.

Materials. Forty-five consonant-vowel-consonant stimuli were selected for each of eight conditions (see Appendix 1). The conditions were created by orthogonally combining two levels of (1) lexicality (word and nonword), (2) log-frequency-weighted similarity neighbourhood density (high and low), and (3) phonotactic probability (high and low). Log-frequency-weighted similarity neighbourhoods were computed by comparing a given phonemic transcription (constituting the stimulus) to all other transcriptions in an on-line version of Webster's Pocket Dictionary (Luce & Pisoni, 1998), a 20,000 word on-line lexicon containing computer-readable phonemic transcriptions and frequency counts based on Kucera and Francis (1967). A neighbour was defined as any transcription that could be converted to the transcription of the stimulus by a one phoneme substitution, deletion, or addition in any position. The log frequencies of the neighbours were then summed for each word and nonword, rendering frequency-weighted neighbourhood density (FWND) measures.

Two measures were used to determine phonotactic probability: (1) positional segment frequency (how often a particular segment occurs in a position in a word) and (2) positional biphone frequency (segment-to-segment co-occurrence probability). These metrics were also computed based on Webster's Pocket Dictionary.

All conditions were matched across shared levels of a given variable (e.g., all high phonotactic probability conditions had approximately equal mean probabilities). In addition, all four word conditions were matched on log frequency and all eight word and nonword conditions were matched on stimulus duration. Omnibus F tests and pairwise comparisons resulted in no significant differences among matched conditions (all ps $> .05$). Stimulus statistics are shown in Table 1.

In addition to the manipulated variables (neighbourhood density and phonotactic probability), five other statistics were computed for the word and nonword stimuli: unweighted neighbourhood density, average neighbourhood frequency (log), isolation point (see Marslen-Wilson &

TABLE 1
Stimulus statistics

Lexicality	*Condition**	*Average log frequency*	*Average FWND***	*Average product of phoneme probabilities*	*Average product of biphone probabilities*	*Average duration (msc)*
Words	HD-HP	2.4	47	1.3×10^{-4}	1.6×10^{-5}	505
	HD-LP	2.2	46	0.4×10^{-4}	0.4×10^{-5}	529
	LD-HP	2.2	27	1.4×10^{-4}	1.5×10^{-5}	495
	LD-LP	2.3	28	0.2×10^{-4}	0.4×10^{-5}	505
Nonwords	HD-HP	-	46	1.4×10^{-4}	1.4×10^{-5}	506
	HD-LP	-	43	0.5×10^{-4}	0.6×10^{-5}	502
	LD-HP	-	27	1.6×10^{-4}	2.0×10^{-5}	493
	LD-LP	-	26	0.4×10^{-4}	0.4×10^{-5}	505

Lexicality	*Condition**	*Average density (unweighted)*	*Average NHF*** (log)*	*Average isolation point (phonemes)*	*Average cohort size*	*Average cohort frequency (log)*
Words	HD-HP	20	2.4	3.0	624	3.0
	HD-LP	19	2.4	3.0	496	2.9
	LD-HP	12	2.2	3.0	624	3.0
	LD-LP	12	2.3	3.0	523	2.9
Nonwords	HD-HP	20	2.3	2.6	650	3.0
	HD-LP	18	2.4	2.2	460	2.8
	LD-HP	12	2.2	2.5	608	3.0
	LD-LP	12	2.2	2.3	524	2.9

* H, high; L, low; D, density; P, phonotactics.
** Frequency-weighted (log base 10) neighbourhood density.
***Neighbourhood frequency.

Welsh, 1978), average cohort size, and average cohort frequency (log). "Isolation point" refers to the point at which each word or nonword stimulus diverges from all possible words in the lexicon, yielding either a single possible word (uniqueness point), or no possible words (nonword point; see Marslen-Wilson 1980), respectively. All five statistics were computed using Webster's Pocket Dictionary. The values for these statistics as a function of condition are shown in the lower panel of Table 1.

Unweighted density and average neighbourhood frequency were computed to ensure that conditions high in FWND have *both* high density *and* high neighbourhood frequency, and that low FWND conditions have low density and neighbourhood frequency. Inspection of the values for unweighted density reveals that the high FWND conditions have more neighbours, irrespective of frequency, than the low FWND conditions

($F(1,352) = 510.50$, $p < .05$). In addition, high FWND conditions have, on the average, higher frequency neighbours than low FWND conditions ($F(1,352) = 34.70$, $p < .05$). Most important, however, none of the word or nonword conditions are anomalous in terms of unweighted density or average neighborhood frequency.

Cohort statistics were computed to ensure that any observed effects could not be attributed exclusively to variations in cohort structure. Analysis of isolation points as a function of condition revealed significant effects of lexicality and phonotactics: Words have later isolation points than nonwords ($F(1,352) =309.18$, $p < .05$) and stimuli with high phonotactic probabilities have later isolation points than stimuli with low phonotactic probabilities ($F(1,352) =17.27$, $p < .05$). (The latter effect was due entirely to the nonwords.) Note that the covariation of phonotactic probability and isolation point works against our hypothesis regarding the effects of phonotactics: Later isolation points should be associated with *slower* reaction times (e.g., Marslen-Wilson & Welsh, 1978), whereas higher phonotactic probability should be associated with *faster* processing.

Analyses of average cohort size and frequency revealed that stimuli with high probability phonotactic patterns had larger cohorts with more frequent members ($F(1,352) = 19.47$, $p < .05$ and $F(1,352) = 29.80$, $p < .05$). Both effects reflect the positive correlation in the language between number of overlapping words and segmental frequency, and both effects should militate against predicted effects of phonotactic probability. However, once again, none of the conditions for either the words or nonwords prove anomalous according to any of the cohort measures.

The word and nonword stimuli were recorded by a trained speech scientist, low-pass filtered at 10 kHz, and digitised 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.

Procedure. The stimuli were presented to participants for speeded same-different judgements, with time to respond *same* constituting the primary dependent variable. *Different* trials constituted fillers and were not analysed. Reaction times in this task have previously proven sensitive to the variables under scrutiny (Vitevitch & Luce, 1999).

Each participant was seated at a testing station equipped with a pair of headphones and a response box. Presentation of stimuli and response collection was controlled by computer. Participants were presented with two spoken stimuli at a comfortable listening level and were instructed to respond *same* or *different* as quickly and as accurately as possible by pressing appropriately labelled buttons. *Same* responses were made with the dominant hand. The inter-stimulus 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. The words and nonwords were presented to separate groups of participants. Twenty participants were presented with the words and 25 with the nonwords. Half of the trials consisted of two identical stimuli (constituting *same* trials) and half of the trials consisted of different stimuli. No participant heard a given stimulus on more than one trial. All different trials consisted of filler items matched to the targets in terms of phonotactics and frequency (for words).

Prior to the experimental trials, each participant received 12 practice trials. These trials were used to familiarise the participants with the task and were not included in the final data analysis.

Results and discussion

The mean reaction times in ms for correct *same* responses are shown in Figure 1. Two (Density) $\times$ 2 (Phonotactic Probability) ANOVAs for words and nonwords were performed for participants (F_1) and items (F_2). Responses resulting from reaction times less than 200 ms and greater than 1200 ms were scored as incorrect. Five words and four nonwords were excluded because they failed to reached a predetermined level of accuracy or produced mean reaction times 2.5 standard deviations above the mean for all items in a given condition. Unless otherwise noted, all significant effects had p values of .05 or less. Accuracy was above 94% for all conditions and produced no significant results.

High density words ($\overline{X} = 708$) were responded to more slowly than low density words ($\overline{X} = 688$; $F_1(1, 19) = 21.32$ and $F_2(1, 171) = 6.09$). High probability words ($\overline{X} = 689$) were responded to more quickly than low probability words ($\overline{X} = 707$; $F_1(1, 19) = 6.68$ and $F_2(1, 171) = 4.17$). The interaction between density and phonotactic probability was not significant ($F_1(1, 19) = 3.92$ and $F_2(1, 171) = 2.40$).

For nonwords, the effect of density was significant by participants ($F_1(1, 24) = 4.827$) but not items ($F_2(1, 172) = 1.34$). The effect of phonotactic probability was not significant (both Fs < 1), nor was the interaction of density and phonotactic probability significant ($F_1(1, 24) = 2.27$ and $F_2(1, 172) = 1.06$).

The results for the *words* reveal simultaneous inhibitory effects of neighbourhood density and facilitative effects of probabilistic phonotactics, demonstrating that—for words—sublexical effects of component probability have effects above and beyond those of lexical density. These data are most consistent with recognition models positing the operation of distinct sublexical and lexical units (such as Shortlist, TRACE, ART-PHONE, or PARSYN).

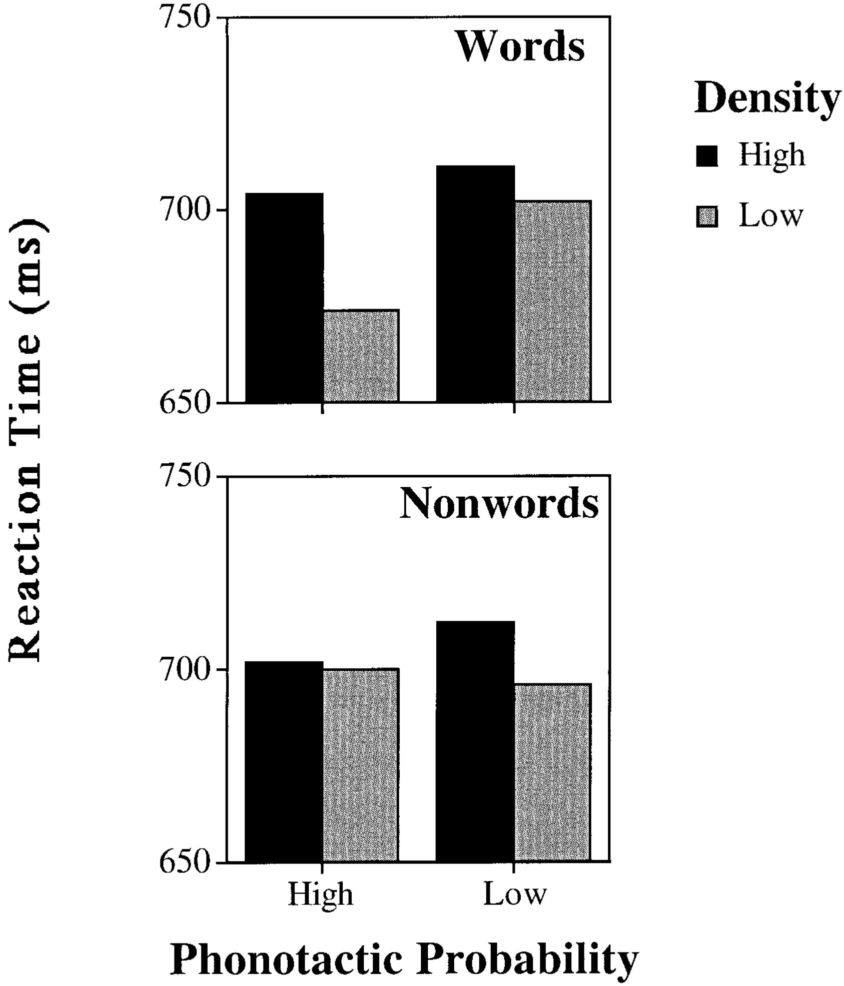

Figure 1. Same-Different reaction times (ms) for words and nonwords as a function of density (dark vs. light bars) and phonotactic probability (x axis).

On the other hand, the *nonwords* failed to show reliable effects of either density or phonotactic probability, in contrast to previous findings demonstrating effects for nonwords of both probabilistic phonotactics (in same-different matching) and neighbourhood density (in lexical decision; Vitevitch & Luce, 1999). Comparison of reaction times for words and nonwords, shown in Figure 2, suggests that the failure to observe the predicted data pattern for the nonwords may lie in *one* anomalous condition. In three of the four density-probability conditions, reaction times were virtually identical for words and nonwords: (1) high density-

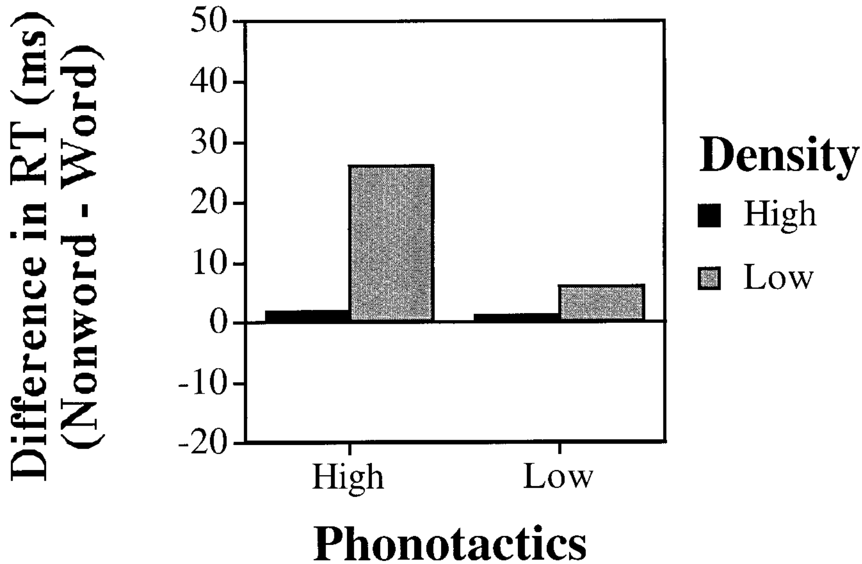

Figure 2. Mean differences in reaction time between words and nonwords as a function of density (dark vs. light bars) and phonotactic probability (x axis).

high probability (Δ reaction time = 2 ms, both Fs < 1), (2) high density-low probability (Δ reaction time = 1 ms, both Fs < 1), and (3) low density-low probability (Δ reaction time = 6 ms, both Fs < 1). However, a marked difference between words and nonwords was obtained for the low density-high probability condition: Nonwords in this condition were responded to 26 ms slower than words ($F_1(1, 43) = 13.23$ and $F_2(1, 88) = 4.37$). We speculate that if nonwords in the low density-high probability condition had behaved as expected, we would have observed the predicted pattern of phonotactic facilitation and neighbourhood competition.

One possible reason for the observed nonword data pattern is that neighbourhood density and phonotactic probability do not always combine in a simple additive, linear fashion. Some current connectionist models suggest that spoken word recognition is the result of complex interactions among representations of various sizes or at multiple levels (McClelland & Elman, 1986; Norris, 1994; Vitevitch & Luce, 1999). Such processing interactions may produce effects that are not predicted by statistics that independently estimate lexical and sublexical activation and competition (i.e., neighbourhood density and probabilistic phonotactics). For example, the potentially anomalous result for the low density-high probability condition may have resulted from an underestimation of the degree of lexical competition. Lessened intralexical inhibition due to the relatively lower number of competing neighbours in low density neighbourhoods, coupled with heightened activation of the neighbours based on their higher phonotactic probabilities, may have produced particularly severe competitive environments for these nonwords. Moreover, the lack of a single lexical representation consistent with the input may have further exaggerated the effects of lexical competition, given that no dominant representation would gain an immediate foothold and suppress activation of its competitors. Thus, the combined effects of (1) a low density neighbourhood, (2) high probability sublexical representations, and (3) the lack of a single lexical representation providing an exact match to the input may have combined to produce a particularly problematic processing environment.

To determine if our statistical measures of neighbourhood density and sublexical probability had indeed underestimated lexical competition for the nonwords in the low density-high probability condition (as suggested by the comparison of the word and nonword data), we conducted a second experiment in which we estimated the degree of lexical activation evoked by our nonwords somewhat more directly than relying on inferences based on corpus searches. Specifically, we asked participants to generate *similar sounding* words (or lexical neighbours) to each of the nonwords used in Experiment 1 (see Greenberg & Jenkins, 1964; Cutler, Sebastián-Gallés, Soler-Vilageliu, & van Ooijen, 2000). We then computed a measure of *entropy* over the word responses to index the number of different lexical items activated by a given nonword. Increases in entropy reflect increases in the number of different words to which a nonword is similar (as measured by this neighbour generation task). Once again, the resulting measure of entropy provides a *behavioural*, rather than purely *statistical*, estimate of lexical competition that may reflect processing interactions inadequately captured by our independent measures of neighbourhood density and phonotactic probability. After collecting the entropy values for the nonwords, we reanalysed the reaction times for the nonwords in Experiment 1 as a function of entropy.

EXPERIMENT 2

Method

Participants. Twenty-one English-speaking adult participants were recruited from the University at Buffalo community. All participants reported no history of a speech or hearing disorder.

Materials. The stimuli consisted of the nonwords used in Experiment 1.

Procedure. Each participant was seated at a testing station equipped with a pair of headphones with an attached microphone. Presentation of stimuli and response collection was controlled by computer. Participants were presented a spoken nonword at a comfortable listening level and were instructed to say aloud, as quickly as possible, a real word that sounded like the nonword stimulus. Responses were recorded on audiotape for later analysis.

Prior to the experiment proper, participants read examples of stimuli (“meech”) and a few possible appropriate responses (“each”, “me”, “beach”, “breach”, or “beseech”), and responded to 10 spoken nonwords as practice trials.

Results and discussion

Ninety per cent of the obtained responses were real words. Mean reaction time to produce these responses was 1749 ms. Table 2 shows the most common word responses as a function of phonemic overlap with the target nonword. Seventy-one per cent of the responses involved one-segment substitutions, suggesting that our neighbourhood metric (based, in part, on phoneme substitutions) should have been capable of capturing at least gross differences in neighbourhood density for spoken nonwords, a prediction not supported by the results of Experiment 1.

As an additional index of lexical activation, entropy values were computed for each nonword based on the word responses. High entropy values indicate that a nonword evoked many different word responses; low entropy values are associated with nonwords that produced a small number of different word responses.

TABLE 2

Percentages of word responses to nonwords in the neighbour generation task as a function of segmental overlap.

Example target nonword: /fin/		
Example word response	*Change*	*Percentage of word responses**
feet	Final consonant	34%
mean	Initial consonant	27%
phone	Vowel	10%
foam	Vowel + final consonant	8%
meat	Initial and final consonant	7%
bin	Initial Consonant + Vowel	3%

* The 11% of responses not shown in this table consisted of a diverse set of categories (additions of single segments, additions of syllables, etc.), none of which individually accounted for more than 3% of the total responses.

Each nonword stimulus was designated as belonging to high or low entropy categories based on a median split of the rank-ordered entropy values. The nonwords were then assigned to one of eight conditions, produced by combining two levels of entropy, density, and phonotactic probability. In order to match the resulting cells on stimulus duration and lexical statistics, we deleted 26 stimuli, leaving 83 high and 71 low entropy nonwords. The numbers of stimuli per cell (and examples) for the high entropy items were: High density-high phonotactics, $N = 25$ (/b æ b/); high density-low phonotactics, $N = 15$ (/fut/); low density-high phonotactics, $n = 20$ (/bɪv/); and low density-low phonotactics, $N = 23$ (/s æ θ/). The numbers of stimuli per cell (and examples) for the low entropy items were: High density-high phonotactics, $N = 16$ (/f i n/); high density-low phonotactics, $N = 25$ (/m ɔ t/); low density-high phonotactics, $N = 10$ (/h ɑ m/); and low density-low phonotactics, $N = 20$ (/ʃ u l/). Omnibus F tests and pairwise comparisons resulted in no significant differences among matched conditions on frequency-weighted neighbourhood density, probabilistic phonotactics, or stimulus duration (all Fs < 1.0).

We ran participant and item ANOVAs on the high and low entropy nonwords as a function of density and probabilistic phonotactics. The results of this post-hoc analysis of the nonword reaction times obtained in Experiment 1 are shown in Figure 3.

For the low entropy nonwords, a marginal effect of density was obtained by participants ($F_1(1,24) = 3.85$, $p = .06$) but not items ($F_2(1,67) = 2.1$). High phonotactic probability nonwords ($\overline{X} = 682$) were responded to more quickly than low phonotactic probability nonwords ($\overline{X} = 702$; $F_1(1,24) = 6.12$ and $F_2(1,67) = 4.39$). The interaction of density and phonotactic probability was not significant ($F_1(1,24) = 1.53$ and $F_2 < 1$).

For the high entropy nonwords, no significant effects of density (both Fs < 1) or phonotactic probability ($F_1(1,24) = 2.00$ and $F_2(1,79) = 1.13$) were obtained. The interaction of density and phonotactics was significant by participants ($F_1(1,24) = 4.46$) but not items ($F_1(1,79) = 1.79$).

Partitioning the nonword stimuli from Experiment 1 according to the entropy values obtained in Experiment 2 reveals that low entropy nonwords exhibit the expected facilitative effect of phonotactic probability. There was also a trend toward an inhibitory effect of neighbourhood density. (The reduced statistical power of this post-hoc analysis may have made this somewhat weaker effect for nonwords more difficult to detect.) On the other hand, high entropy nonwords exhibited no significant effects of either variable. These results suggest that neighbourhood density and phonotactic probability are—at least for nonwords—mediated by the strength of activation of specific similar representations.

Comparison of reaction times across entropy condition (high vs. low), shown in Figure 4, reveals that three of the four conditions exhibited

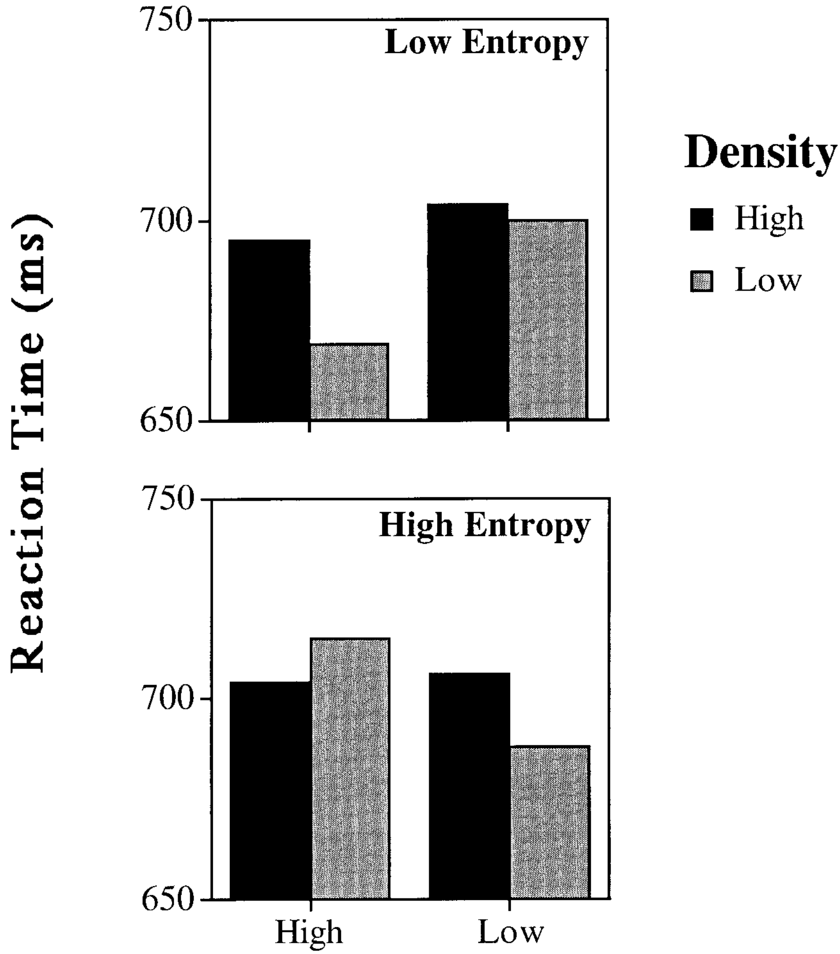

Figure 3. Same-Different reaction times (ms) for low and high entropy nonwords as a function of density (dark vs. light bars) and phonotactic probability (x axis).

virtually no differences as a function of entropy: (1) high density-high probability (Δ reaction time = 9 ms, both Fs <1), (2) high density-low probability (Δ reaction time = 2 ms, both Fs <1), and (3) low density-low probability (Δ reaction time = 12 ms, $F_1(1,24) = 1.33$ and F_2 <1). However, a marked difference between high and low entropy was obtained for the low density-high probability condition. In particular, high entropy nonwords in this condition were responded to 46 ms slower than low entropy nonwords ($F_1(1,24) = 18.64$ and $F_2(1,29) = 7.12$).

In summary, the results of the entropy analysis strongly suggest that our original statistical measures of neighbourhood density and phonotactic

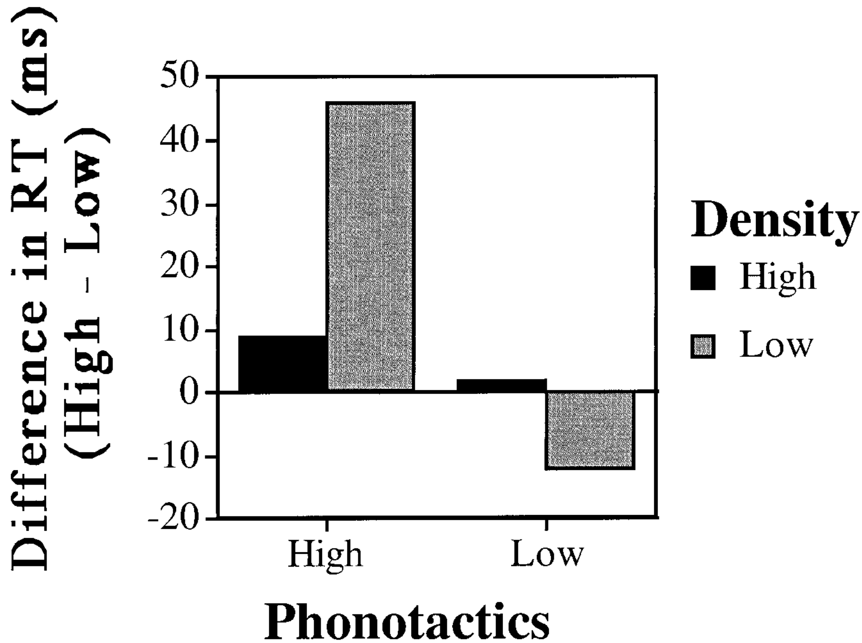

Figure 4. Mean differences in reaction time between high and low entropy stimuli as a function of density (dark vs. light bars) and phonotactic probability (x axis).

probability failed to predict the degree of lexical competition for certain of the nonwords in the low density-high probability condition. When only low entropy nonwords in all conditions were examined, a data pattern emerged that was virtually identical to that observed for words in Experiment 1. However, consistent with the hypothesis that certain of the nonwords in the low density-high probability conditions were succumbing to increased lexical competition, high entropy nonwords in this condition were responded to significantly more slowly than low entropy nonwords.

GENERAL DISCUSSION

Our original intent was to unconfound similarity neighbourhood density and phonotactic probability in an attempt to demonstrate their simultaneous effects on processing. Indeed, we were successful at demonstrating *both* facilitative effects of phonotactic probability and inhibitory effects of lexical competition for *words*. Thus, although lexical competition may typically dominate processing for real words (Vitevitch & Luce, 1999), phonotactic probability also has demonstrable and predictable effects on processing speed.

Our efforts at demonstrating effects of density and phonotactic probability for nonwords did not (at least at first) meet with comparable success. When we examined nonwords that were closely matched to real words on density and phonotactics, no reliable effects of either variable were observed. Comparison of the word and nonword data revealed a correspondence between processing times in all experimental conditions except one: Nonwords in the low density-high probability condition produced longer-than-expected reaction times.

Subsequent analyses of the nonword data revealed that effects of lexical competition appear to have been underestimated for a portion of the nonwords in the low density-high probability condition. When lexical competition was assessed behaviourally using the neighbour generation task, those nonwords having the fewest neighbours (low entropy items) behaved as predicted. However, our post-hoc analysis revealed that high entropy nonwords in the low density-high probability condition—that is, those nonwords that evoked multiple word responses—were processed more slowly than predicted based on our *statistical* measures of neighbourhood density and phonotactic probability. Thus, our measure of entropy identified a set of nonwords in the low density-high probability condition that apparently produce stronger lexical competition than predicted by our statistical measures.

Why, then, did our statistical measures of lexical competition and phonotactic probability accurately predict performance in all but one of our eight original conditions? We propose that lexical competitors, whose strengths are determined by the synergistic effects of sublexical activation and lexical competition, may exert influences on processing above and beyond the simple combined, additive effects of sublexical probability and neighbourhood density. Recall that the low density-high probability condition, which exhibited the greatest difference as a function of lexicality (Experiment 1) and entropy (Experiment 2), contains those nonwords having few lexical neighbours but highly probable sublexical components. In this unusual situation, in which the normal positive correlation of density and phonotactic probability is broken, processing interactions between lexical and sublexical representations may give rise to heightened effects of lexical competition not predicted by our standard measures of density or probabilistic phonotactics.

In particular, we propose that nonwords high in entropy in the low density-high probability condition strongly activate a handful of lexical items whose attraction to or support by the input pattern is particularly high and whose competition is severe. In short, low lexical density and high sublexical probability appear to combine synergistically to make these particular nonwords vulnerable to specific, highly similar competing lexical items. Work is currently underway to determine the precise circumstances under which low density-high probability stimuli give rise to the high entropy situations identified by our neighbour generation task. Nonetheless, the current results point to the need to consider the effects of lexical and sublexical statistics in the context of potentially complex processing interactions.

In short, our principal claim is that a simple combination of effects of lexical competition and phonotactic probability may fail to capture nonlinear combinations of the effects of activation and competition at lexical and sublexical levels of representation for nonwords. We speculate that similar results may be obtained for real words that lack strong activation of form-based lexical representations (e.g., low frequency words). Nonetheless, we believe that the present results support the previously hypothesised roles of lexical and sublexical representations in spoken word recognition, while at the same time suggesting a complex interplay of density and probabilistic phonotactics.

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APPENDIX

Word and nonword stimuli in each of the density-probability conditions*

Word Stimuli				Nonword Stimuli			
High-High	High-Low	Low-High	Low-Low	High-High	High-Low	Low-High	Low-Low
bol	bæθ	bɑb	bɛg	bem	bUd	bɑɪm	bep
but	bɔt	bɑm	bUk	bæb	bʌtʃ	bɪv	dædʒ
dem	dʌg	bɪb	dɪʃ	dek	ded	bæv	dætʃ
dæd	dum	bim	fez	dɪz	fɑɪd	dɑb	dUs
dʌd	fek	dɑk	fɪʃ	dod	fedʒ	dɑp	fɛg
fɑɪl	fem	dɑl	fUl	dʌs	fut	dɛp	fɪdʒ
fɛd	fɔt	dɛf	fUt	dʌt	ged	dɪv	fɔs
fɛl	gen	dɔn	gis	fɪd	ges	dæl	gɑɪs
fel	get	dos	gɔn	fɪk	hɑɪm	fɑɪk	hɪð
fæd	hid	fɪg	hɑUl	fin	hed	fɑm	hɪʒ
fon	hip	fok	hɛdʒ	fɪp	hem	fɛp	hɔn
ful	hɪtʃ	fom	hæf	fɪs	hɪg	fim	hʌp
fʌn	lem	f ′n	hop	fʌt	hik	fæp	hus
gɪr	lod	fʌs	hup	gɑɪn	him	fæv	kitʃ
gor	læg	gɛs	kev	gɛr	lep	fos	log
hel	lʌk	gæs	lɛg	hɑɪn	lɪg	gɪs	lUn
hʌl	mez	hɑɪr	lob	hɪv	lim	hɑm	lov
hʌm	mit	hɛm	læf	hæb	lʌd	hɪb	l ′s
kɑd	mɔl	hɛn	lɔn	kæŋ	mɑUn	hos	mɑɪv
kip	nɑɪt	hom	lus	koz	mɑUt	hʌs	mɑUl
kom	nit	h ′s	mɛʃ	lɑd	mep	kob	mɪʃ
lɑɪs	nʌt	kɑn	mætʃ	lɑr	mev	lɑm	miv
lɪd	pitʃ	kɪs	mud	lot	mip	lɑn	mæŋ
lɪp	piz	lɪm	nis	lʌs	mɔt	lɛp	mum
lɪt	rɑɪd	lɪv	nʌl	mɛd	nek	læl	nɑɪr
mek	red	l ′n	nun	mok	nes	lær	num
min	redʒ	lʌl	pɑUt	mʌn	nik	mim	pɑtʃ
mæd	rez	mɑb	pev	nɑr	pUk	mæb	pʌz
mun	rif	mɑp	pæθ	pɛd	rɔl	mæv	rɑɪb
nɑɪn	rɪŋ	mɪθ	pUl	pem	ʃɑr	mom	rɪʃ
non	sedʒ	mʌd	rɑɪp	pæz	ʃes	nɪm	roʃ
nʌn	ʃek	nɑk	rɪdʒ	pʌm	ʃet	nɪs	ruk
pɑr	ʃɛr	nɛk	ræθ	rem	ʃɪk	næs	rʌz
ped	ʃik	pɑm	rotʃ	rɛt	siθ	pɑb	ʃɪm
pen	ʃit	pɛk	rʌg	ræb	sitʃ	pɪm	sæθ
pik	ʃæk	pop	ʃɑɪn	rok	ʃok	pæv	ʃom
pæd	sʌŋ	p ′s	sef	rʌd	ted	p ′d	ʃ ′n
rot	tɑɪd	rɛk	ʃɛf	ʃæn	tip	rɑl	sudʒ
ʃɪn	tɑl	rɪb	ʃɪp	s ′d	tʃek	rɪv	ʃUl
sis	tem	sɑʌr	ʃon	s ′k	tʃel	ræv	tædʒ
sɔt	tʃɪr	tɑp	tep	sʌg	tʃɛt	sʌv	tʃɪm
tɑɪl	tʃit	tɪp	tɔt	tɑɪs	tʃʌn	tɪd	tʃin
tel	tʃor	tæb	tʃɛk	ten	tud	tæv	tʃæs
tol	tum	tær	tʃɪl	tʌl	tup	tos	tʃos
tʃɪn	vel	væn	tʃok	vɪl	vet	væs	vit

*High-High refers to high density-high probability, High-Low refers to high density-low probability, etc.