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The Effect of Phonological Neighborhood Density on Vowel Articulation

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Abstract

Recent literature suggests that phonological neighborhood density and word frequency can affect speech production, in addition to the well-documented effects that they have on speech perception. This article describes 2 experiments that examined how phonological neighborhood density influences the durations and formant frequencies of adults' productions of vowels in real words. In Experiment 1, 10 normal speakers produced words that covaried in phonological neighborhood density and word frequency. Infrequent words with many phonological neighbors were produced with shorter durations and more expanded vowel spaces than frequent words with few phonological neighbors. Results of this experiment confirmed that this effect was not related to the duration of the vowels constituting the high- and low-density words. In Experiment 2, 15 adults produced words that varied in both word frequency and neighborhood density. Neighborhood density affected vowel articulation in both high- and low-frequency words. Moreover, frequent words were produced with more contracted vowel spaces than infrequent words. There was no interaction between these factors, and the vowel duration did not vary as a function of neighborhood density. Taken together, the results suggest that neighborhood density affects vowel production independent of word frequency and vowel duration.

Keywords

phonological neighborhood density; word frequency; vowels; acoustic measurements; adults

Knowledge of the phonological structure of language involves knowledge of both the categorical units of language and their phonetic outcomes. This relation is highly complex. Instances of the same phonemic category may be realized with qualitatively different phonetic outcomes in different words. For example, it is well known that sounds may coarticulate with adjacent sounds, so that the /s/ in words like *sweet* is qualitatively different

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from the /s/ in *seat*, due to the accommodations that are made for the lip rounding of the upcoming /w/ (Munson, 2004). Furthermore, the articulation of a sound may vary as a function of the prosodic structure in which it is embedded: The laryngeal gesture associated with the sound /k/ in prevocalic position is different depending on whether the subsequent vowel receives stress (Fourakis, 1986). Phonetic outcomes are also related to factors other than segmental and prosodic structure. Phoneme production may be modified due to changes in the demands of a speaking task, such as when a person hyperarticulates phonemes in noisy environments or when speaking to someone who is presumed to need an atypically clear signal (Bradlow, 2002).

One factor that affects phoneme articulation is phonological neighborhood density. In the most commonly used metric, *phonological neighborhood density* refers to the number of words that differ from a target word by a single phoneme. Monosyllabic words vary greatly in the density of the neighborhoods in which they reside. The word *cat* has a large number of phonological neighbors, including *scat*, *at*, *coat*, and *cap*. The word *choice* has relatively fewer neighbors, such as *voice* and *chase*. Neighborhood density strongly influences spoken-word recognition. Luce and Pisoni (1998) reviewed studies showing that infrequently used words with dense phonological neighborhoods (henceforth *lexically difficult* words) are identified less rapidly and less accurately than are frequently used words with sparse neighborhoods (*lexically easy* words). This effect can be termed *lexical competition*, as the perceptual difficulties associated with lexically difficult words are presumed to be due to the words in dense phonological neighborhoods competing with one another as potential responses in perceptual tasks.

These results have been used to argue for a model of the lexicon in which words are organized in terms of their phonological similarity. If indeed the lexicon is organized this way, the same factors should predictably influence speech production. Presumably, the competition effects that influence perception might also influence the selection, encoding, and articulation of lexical items in speech production, although not necessarily in the same direction. Indeed, at least one study has found an influence of lexical competition on speech production. Vitevitch (2002) found that pictures representing words in dense phonological neighborhoods were named more quickly than those representing pictures in sparse neighborhoods. In a second experiment, Vitevitch found fewer speech errors for words in sparse neighborhoods than for words in dense neighborhoods.

A recent study by R. Wright (2004) suggested that phonological neighborhood density influences the phonetic realization of phonemes. R. Wright (2004) analyzed the distribution of vowels in the F1/F2 space and found that vowels in lexically difficult words were produced further from the euclidian center of the F1/F2 space than those in easy words. Thus, the vowels in the lexically difficult words were more physically distinct from one another and, presumably, more easily discriminated than those in the lexically easy words. R. Wright (2004) interpreted this result by saying that talkers actively modify their articulation of phonemes in lexically difficult words to maximize their distinctiveness. This is consistent with Lindblom's (1990) hypospeech and hyper-speech theory of speech production, which argues that talkers actively modify their articulation in different tasks and speaking environments to maintain an adequate level of intelligibility. R. Wright's (2004) results suggest that talkers have a tacit awareness of the perceptual difficulties associated with lexically difficult words and that they subtly modify their articulation to make these words easier for listeners to perceive.

The interpretation of R. Wright's (2004) results could be affected by two factors. First, the differences in vowel expansion may have been associated with differences in vowel duration. Moon and Lindblom (1994) demonstrated that vowel duration is positively correlated with vowel expansion: Shorter vowels tend to be produced closer to the euclidian center of the F1/F2 space than longer vowels. This effect is sometimes called *duration-dependent undershoot* or *duration-dependent overshoot*. Vitevitch (2002) showed that naming latencies for lexically difficult words were shorter than those for lexically easy words. This lexical competition effect might also have slowed the production of those words, making the vowels in the lexically difficult words longer than those in the lexically easy words. Thus, R. Wright's (2004) result may have been an artifact of the vowels embedded in lexically easy words being shorter than those in the lexically difficult words. Consequently, the longer durations of the vowels in lexically difficult words may have contributed to their expansion rather than intentional modification to maximize lexical distinctiveness. R. Wright (2004) does not report the duration of the vowels in high- and low-density words.

A second factor to consider is the relative contribution of word frequency and neighborhood density to patterns of vowel reduction. In the stimuli used by R. Wright (2004), neighborhood density covaried with word frequency: The less expanded low-density words were also higher in word frequency than the more expanded high-density words. As documented by Bybee (2001), high-frequency words are more likely to undergo phonological reductions than low-frequency words. For example, the schwa in the second syllable of high-frequency trisyllabic words like *memory* is more likely to be deleted than in the phonologically similar low-frequency word *mammary*. At the phonetic level, reduction may be manifested as contracted vowel spaces. The contracted vowel spaces for the low-density words in R. Wright's (2004) study may have been a reflection of their high frequency of usage rather than their neighborhood density.

The purpose of this article is to further examine the influence of phonological neighborhood density on vowel production. It contains two experiments. The first experiment used a subset of R. Wright's (2004) stimuli to examine whether the combined influence of neighborhood density and word frequency on vowel articulation was due to vowel duration. The second experiment examined whether word frequency and neighborhood density had separate effects on vowel articulation. Results of the two experiments suggest that the effect of neighborhood density on vowel articulation is unrelated to vowel duration and is independent from word frequency.

Experiment 1: Neighborhood Density and Vowel Duration

Experiment 1 examined the duration and vowel-space expansion of vowels in lexically easy and lexically difficult words. Specifically, it examined the vowel duration and vowel-space expansion for words that differed in lexical difficulty, to determine whether expanded vowel spaces were associated with lexically difficult words or with words that had longer vowels more generally. If the expanded vowel spaces associated with lexically difficult words were due to their increased duration, then one would predict strong, consistent correlations between those measures. If the expansion of vowel spaces was associated with lexical competition, then lexically difficult words would predictably evidence more expanded vowel spaces regardless of their duration.

Method

Participants

Ten individuals from the University of Minnesota community participated in this study. Eight of the participants were women, and 2 were men. They ranged in age from 20;11 (years;months) to 38;9 (*M* = 26;3, *SD* = 6;2). All participants were native speakers of English. Participants reported no history of speech, language, or hearing disorders, and all participants passed a pure-tone hearing screening at 0.5, 1, 2, and 4 kHz at 20 dB HL (American National Standards Institute, 1989) in one ear, or they reported a normal audiometric evaluation within the month before the experiment. All had normal or corrected-to-normal vision. Participants received compensation of $10 per hour for their participation in the entire study.

Stimuli

Thirty consonant, vowel, consonant (CVC) words, listed in Table 1, were used as stimuli. The words were taken from the Hoosier Mental Lexicon (HML; Pisoni, Nusbaum, Luce, & Slowiaczek, 1985), an online version of Webster's pocket dictionary. Fifteen of these were lexically difficult words; the remaining 15 were lexically easy words. All of the words in this study had been rated to be highly familiar to a group of Indiana University undergraduate students, as indicated by a mean familiarity rating of greater than 6.8 on an equal-interval 7-point scale (Pisoni et al., 1985). Furthermore, the two types of words differed in their perceptibility; the difficult words used in this study had been identified less accurately than easy words across a range of experimental tasks (Luce & Pisoni, 1998).

The six vowels in the words selected for this study were the ones found by R. Wright (2004) to be produced differently as a function of the frequency and phonological neighborhood density of the words in which they were embedded. As in the study by R. Wright (2004), the vowels were not distributed uniformly within the two lists. There were more low vowels (/a/, /æ/) than mid (/o/) and high (/i/, /ɪ/, /u/) vowels. Vowel qualities were not distributed randomly in lexically easy and lexically difficult words, and the distribution of vowels on the two lists was a consequence of choosing word lists that were also matched for final-consonant voicing.

Because vowel articulation is related to vowel duration, the two lists also were balanced for characteristics that might influence vowel duration. Each list contained two words with /i/, three words with /ɪ/, three words with /æ/, four words with /a/, two words with /o/, and one with /u/; each of these vowels differs in its intrinsic duration. The two lists did not differ significantly in the distribution of words ending in voiced obstruents, voiceless obstruents, or voiced sonorant consonants, $\chi^2(2, N = 30) = 0.7$, $p > .05$, all of which had been shown to affect vowel duration (e.g., House & Fairbanks, 1953).

Data Collection

For the speech production task, participants were given a stack of 3 × 5 cards in which the target words were printed in 48-point Times New Roman font. The order of the cards was randomized and read aloud once, then rerandomized and read a second time. Participants read the words at a rate of approximately 1 word per second.

The data were recorded on a Roland VS-890 digital workstation, at a sampling rate of 44.1 kHz, with 16-bit quantization and an anti-aliasing filter with a cutoff frequency of 22.05 kHz. Participants wore an AKG-C420 head-mounted condenser microphone, attached to a Rolls phantom power source. Data were recorded in a quiet laboratory.

Measurement

Data were transferred from the Roland VS-890 to a personal computer for acoustic analysis. The Praat v. 4.0.7 signal-processing software (Boersma & Weenink, 2002) was used for analysis. Before analysis, tokens were excluded if they were produced disfluently or had extraneous noise. The mean number of tokens analyzed per participant was 59 and ranged from 57 to the full set of 60 tokens. The missing tokens were distributed evenly among lexically difficult and lexically easy words.

Vowel duration—The first analysis involved measuring durations of the vowels in both sets of the difficult and easy words. These measures were made while viewing a display with a waveform and a broadband spectrogram with a superimposed linear predictive coding (LPC) formant track. Vowel onset was defined differently depending on the voicing and manner of the initial consonant. When the initial consonant was a voiceless obstruent, vowel onset was defined as the onset of periodic variation in the waveform indicative of vocal fold vibration. When the initial consonant was a voiced obstruent, vowel onset was defined as the onset of a clear formant structure in the broadband spectrogram, indicative of vowel-like resonance. When the initial consonant was /w/, vowel onset was defined as the onset of a steady-state second formant. The definition of vowel offset was also dependent on the manner and voicing of the final consonant. When the final consonant was /n/, vowel offset was defined as point of abrupt discontinuity in the amplitude of the waveform, indicative of the onset of nasal airflow and resonance. When the final consonant was an obstruent, vowel offset was most often defined as the offset of an obvious voiced formant structure in the vowel.

A second person remeasured 11 tokens (2% of the data) to assess measurement reliability. These tokens were equally distributed among the 10 talkers and among the different experimental conditions. The range in duration between these measures and the original measures was −7 to 8 ms; the average absolute difference was 6 ms.

Vowel-space expansion—F1 and F2 at vowel midpoint were measured automatically using an LPC formant-tracking algorithm in Praat. Values that differed by at least 100 Hz from the mean values published by Hillenbrand, Getty, Clark, and Wheeler (1995) were hand-checked to ensure accuracy. As in the study by R. Wright (2004), the formant values were converted to bark values (Zwicker & Ternhardt, 1980) before computing vowel-space expansion. The bark scale is an auditory rather than linear measure of frequency, based on critical bands of sensitivity to frequency differences.

Expansion in the F1/F2 space was measured by means of a method presented by Bradlow, Toretta, and Pisoni (1996). In this method, the expansion for a vowel space is the average euclidian distance of the individual tokens from the center of the vowel space, defined as the average F1 and F2 values. Previous studies on speech intelligibility have found that more intelligible speech or clear speech is associated with expanded vowel spaces (Moon & Lindblom, 1994; Picheny, Durlach, & Braida, 1986). Bradlow et al. (1996) found that the mean euclidian distance measure of vowel-space expansion was a good predictor of intelligibility differences among normal talkers. In addition, R. Wright (2004) found that vowel-space expansion was different for difficult and easy words. For each participant, vowel-space expansion measures were calculated separately for difficult and easy words.

Results

Vowel Duration

A paired-subjects *t* test was used to examine the influence of competition on vowel duration. On average, the lexically easy words were produced with longer vowel durations than were the lexically difficult words (M = 232 ms, SD = 21, for easy words; M = 222 ms, SD = 22, for difficult words). This effect achieved statistical significance, $t(9) = 5.4$, $p < .01$. The group analysis was supplemented with an informal analysis of individual participants' data, to determine whether some individuals produced patterns that were notably different from that of the group. Individual participants' productions mirrored the group pattern: Each produced longer mean vowel durations for lexically easy words than for lexically difficult words. The differences ranged from 2 to 20 ms.

Vowel-Space Expansion

A paired-subjects *t* test was used to examine the effect of lexical difficulty on vowel-space expansion. A significant effect of lexical difficulty was found, $t(9) = -3.5$, $p < .01$. The lexically difficult words were produced with greater vowel-space expansion (M = 2.68 bark, SD = 0.25) than were the lexically easy words (M = 2.57 bark, SD = 0.21), an observation consistent with R. Wright's (2004) findings.

On average, the vowels in Experiment 1 were more expanded than those studied by R. Wright (2004). Figures 1 and 2 illustrate sample vowel spaces for 1 participant. These show the F1/F2 values for individual vowels, as well as the mean F1/F2 for that vowel space, indicated with an *X*. These figures illustrate the group result that vowel expansion was relatively large for lexically difficult words. Moreover, the figures illustrate that the expansion noted among the different conditions was not due merely to one particular vowel. Rather, the differences in expansion affected all of the vowels. These figures also illustrate that the center of the vowel space was not always at the same location. With two within-subjects analyses of variance (ANOVAs), we examined whether F1 and F2 differed significantly as a function of lexical difficulty. None of the differences reached statistical significance at the Bonferroni-corrected alpha level. Thus, the expansion differences among conditions did not appear to be related to changes in the overall location of the individual vowels in the F1/F2 space.

Individual participants' data were again examined to determine the extent to which each talker conformed to the group pattern. In this analysis, not all participants mirrored the group pattern. Eight of the 10 participants produced more expanded vowel spaces for the lexically difficult words than for the lexically easy words. The 2 participants who did not mirror the group difference showed a very small difference in the opposite direction: F04 and F06 both had differences of 0.06 bark. In comparison, the differences for participants whose pattern matched that of the group ranged from 0.07 to 0.40 bark.

Relations Between Duration and Expansion

The final analysis considered the relation between mean vowel duration and expansion, to assess whether the differences between lexically easy and lexically difficult words were due to duration-dependent overshoot or undershoot. Recall that contrary to predictions, vowels in the lexically difficult words were produced with shorter durations than vowels in lexically easy words. Thus, it seemed unlikely that the more compact vowel spaces associated with easy words were due to duration-dependent undershoot. This was confirmed by examining simple correlations (Pearson's r) between measures of expansion and measures of mean duration. When both experimental conditions were examined together, a correlation of −.238 was found; this was not significant at the Bonferroni-corrected $\alpha = .025$ level. Moreover, this correlation was in the opposite-than-predicted direction: The vowel spaces with the shortest mean durations were produced with most expansion. Thus, it seems likely that the mechanisms underlying the duration differences and the expansion differences are different. When each condition was examined separately, correlations were −.035 (lexically difficult words) and −.401 (lexically easy words). Neither correlation reached statistical significance.

Discussion

Experiment 1 demonstrated a relation between lexical competition and vowel production. Lexically difficult words were produced with more expanded vowel spaces than were lexically easy words. This effect did not appear to be related to the durations of the vowels contained in those words, as the vowels in the lexically difficult words were shorter than those in the lexically easy words. Previous research (Moon & Lindblom, 1994) indicates that longer vowels should be associated with greater vowel-space expansion. The finding that more difficult words were produced with greater expansion but shorter duration indicates that vowel duration did not confound the results for expansion; indeed, this makes the interpretation of the vowel-expansion effect more robust.

The most surprising finding in this experiment was that the vowels in lexically difficult words were produced with shorter durations than those in lexically easy words. One potential explanation for this finding has been suggested by Munson (2001). Munson found that sequences of phonemes with high phonotactic probability (i.e., /ft/) are articulated with shorter durations than phonetically similar low-probability sequences of phonemes (i.e., /fk/). In general, lexically difficult words contain higher probability sequences than lexically easy words. Indeed, this was true for the stimuli used in this experiment. Using the method for computing phonotactic probability presented in Munson (2001), the lexically easy words were found to be lower in probability than the lexically difficult words (Wilcoxon $W = 178$, $z = -2.91$, $p < .01$). The apparent effect of neighborhood density on duration may be attributed to phonotactic probability.

Two factors limit the interpretation of the findings of Experiment 1. The first concerns the relative influences of word frequency and neighborhood density on production. In this stimulus set, as in R. Wright (2004), frequency and neighborhood density covaried. The high-density words were also lower in frequency than the low-density words. Using the written-word frequency and neighborhood density counts from the HML (Pisoni et al., 1985), both were found to differ across the two word lists (Wilcoxon $W = 150.5$, $z = -4.06$, $p < .01$, for neighborhood density; Wilcoxon $W = 115.5$, $z = -4.26$, $p < .01$, for frequency). Frequency and neighborhood density may have affected vowel-space expansion independently.

Second, the results of this experiment may have been due, in part, to the phonetic composition of the high- and low-density words. The lists of words were chosen to represent as good a phonetic match as possible. However, there were a number of asymmetries that may have inadvertently affected the results. For example, the low vowel /a/ was always paired with a voiced consonant in the lexically difficult words. This may have led to differences in vowel duration across the two lists.

To address these possible confounds, a second experiment was conducted. For this experiment, a new set of stimuli was selected to vary in both word frequency and in neighborhood density.

Experiment 2: Neighborhood Density and Word Frequency

Experiment 2 was designed to examine the separate effects of frequency and neighborhood density on vowel articulation. By examining these factors separately, the possibility that the effects of neighborhood density on vowel expansion observed in Experiment 1 and in R. Wright (2004) were artifacts of word frequency can be examined. Furthermore, the results can determine whether the differences in vowel duration noted in Experiment 1 were confounded by word frequency.

Method

Participants

Seven of the participants from Experiment 1 and 8 additional adults participated in this experiment. The nine women and 6 men ranged in age from 20;5 to 25;4 (*M* = 22;3, *SD* = 1;3). The participants met the same criteria and were compensated as for Experiment 1.

Stimuli

The stimuli for this experiment are listed in Table 2. They consisted of 20 quadruplets of high- and low-density, high- and low-frequency words. Word frequency was taken from Kučera and Francis (1967), and neighborhood density was taken from the values in the HML (Pisoni et al., 1985). Stimuli were selected by taking a median split of the entire set of CVC words in the HML based on word frequency, then taking a median split within for each of the two lists based on neighborhood density. The average neighborhood density for high-density words was 17.4 (*SD* = 6.1); the average for the low-density words was 3.6 (*SD* = 1.8). The average word frequency for high-frequency words was 148 (*SD* = 157). The average word frequency of low-frequency words was 6.8 (*SD* = 5.2). With a two-factor multivariate analysis of variance, we examined the influence of frequency and neighborhood density category on the continuous measures of these variables and found that they did not interact, $F(1, 76) < 1$, $p > .05$, for both frequency and neighborhood density. That is, the differences in neighborhood density were statistically equivalent for high- and low-frequency words and vice versa.

Each quadruplet contained the same vowel. Within each quadruplet, voicing of the final consonant was consistent across the four items. Moreover, close attention was paid to balancing the manner and voicing of the consonants constituting the four word types across the 20 quadruplets. The four lists of words did not differ significantly in the manner of the initial or final consonants or the voicing of the initial consonant, $\chi^2(6, N = 80) = 1.7$, $p > .05$, for initial-consonant manner; $\chi^2(6, N = 80) = 4.2$, $p > .05$, for final-consonant manner; $\chi^2(3, N = 80) < 1$, $p > .05$, for initial-consonant voicing.

Data Collection

Testing took place in a double-walled sound-treated room. Stimuli were presented on a 17-in. video monitor. Each word was presented 3 times in randomized order, for a total of 240 productions per participant. An additional 80 filler items appeared in the experiment. The experiment was preceded by a practice block consisting of 8 nontest items. The experiment was self-paced; participants pressed a button on a button box to advance items.

The data were recorded on a Marantz CDW300 CD recorder at a sampling rate of 44.1 kHz, with 16-bit quantization and an anti-aliasing filter with a cutoff frequency of 22.05 kHz. Participants wore an AKG-C420 head-mounted condenser microphone with phantom power (Rolls PB23).

Measurement

Data reduction followed the same procedures as those used in Experiment 1 unless noted below. The mean number of tokens analyzed per participant was 239 (*SD* = 1.2) and ranged from 236 to the full set of 240 tokens. The missing tokens were distributed approximately evenly among participants and conditions.

Duration—Vowel durations were measured using similar measurement methods and segmentation criteria as in Experiment 1. A second person remeasured 50 tokens to assess measurement reliability. These tokens were evenly distributed among the 15 talkers and among the different experimental conditions. The range in duration between these measures and the original measures was −11–12 ms; the average absolute difference was 10 ms.

Vowel-space expansion—As in Experiment 1, vowel formants were measured automatically using an LPC algorithm. Values that were greater than 100 Hz away from the mean values reported by Hillenbrand et al. (1995) were hand-checked for accuracy and remeasured when necessary. As in Experiment 1, formant frequencies were converted to the bark scale before analysis, and vowel-space expansion was calculated using the method from Bradlow et al. (1996).

Results

Duration

A two-factor within-subjects ANOVA was used to examine the effects of frequency and neighborhood density on mean vowel duration. A significant main effect of frequency was found, $F(1, 14) = 17.3$, $p < .01$, partial $\eta^2 = .55$. Vowels embedded in high-frequency words were produced with shorter durations ($M = 205$ ms, $SD = 45$) than vowels in low-frequency words ($M = 211$ ms, $SD = 48$). No effect of neighborhood density was found, nor was the interaction between them significant, $F(1, 14) < 1$, $p > .05$, for both tests.

Analysis of individual participants' data showed that 12 of the 15 participants followed the group result by producing longer vowels in low-frequency words than in high-frequency words. The difference ranged from 3 to 15 ms. The remaining 3 participants had differences between 0 and −3 ms.

Vowel-Space Expansion

A two-factor within-subjects ANOVA was used to examine the effects of frequency and neighborhood density on vowel-space expansion. A significant main effect of frequency was found, $F(1, 14) = 18.7$, $p < .01$, partial $\eta^2 = .57$. The vowel spaces associated with high-frequency words were less expanded ($M = 2.69$ bark) than those associated with low-frequency words ($M = 2.84$ bark). In addition, there was a significant main effect of neighborhood density, $F(1, 14) = 5.8$, $p < .05$, partial $\eta^2 = .29$. Although the difference between high- and low-density low-frequency words was larger ($M = 0.11$ bark) than the difference for high-frequency words ($M = 0.05$ bark), this interaction did not achieve statistical significance, $F(1, 14) = 1.1$, $p > .05$. Post hoc tests of significant main effects found that the effect of neighborhood density on vowel-space expansion was significant for both the high- and low-frequency words. Summary data for vowel expansion are shown in Figure 3.

Analyses of individual participants showed that 13 of the 15 participants produced vowel spaces associated with low-frequency words with greater expansion than those associated with high-frequency words (averaged across high- and low-density words). The differences in expansion ranged from 0.04 to 0.34 bark. The remaining 2 participants produced differences of 0.04 and 0.18 bark in the opposite direction. In addition, 10 of the 15 participants produced vowel spaces associated with high-density words with greater expansion than those associated with low-density words (averaged across high- and low-frequency words). The differences in expansion among the 10 participants mirroring the group pattern ranged from 0.04 to 0.31 bark. The remaining participants showed differences in the opposite direction, ranging from 0.01 to 0.08 bark.

Sample vowel spaces for 1 participant are presented in Figures 4 and 5. Figure 4 contains average vowel formants for that speaker's productions of low-frequency, high-density words. Figure 5 contains average vowel formants for that speaker's productions of high-frequency, low-density words. These are the two conditions that showed the greatest differences in vowel-space expansion. As these figures illustrate, the differences in vowel-space expansion were present for most of the vowels studied. That is, there was not simply a single vowel that accounted for the differences in expansion noted between the different conditions.

Relations Between Duration and Expansion

In the final analysis, we considered the relation between mean vowel duration and expansion, to assess the effects of duration on vowel articulation. This was tested by examining Bonferroni-corrected simple correlations (Pearson's r) between measures of expansion and measures of mean duration. When all four experimental conditions were examined together, a correlation of −.194 was found. The associated p value was not significant at the .05 level. When each condition was examined separately, correlations ranged from −.055 to −.238. No correlation reached significance at the .05 level. Thus, although the low-frequency words were associated with longer vowel durations than were the high-frequency words, this did not appear to explain the vowel-space expansion differences between them.

Discussion

Experiment 2 both replicated and expanded on the results of Experiment 1. As in Experiment 1, vowels associated with high-density words were articulated with more expanded vowel spaces than vowels associated with low-density words. Moreover, this effect occurred irrespective of frequency. Both high- and low-frequency high-density words were articulated with more expanded vowel spaces than high- and low-frequency low-density words. In addition, word frequency influenced vowel-space expansion. High- and low-density low-frequency words were articulated with more expanded vowel spaces than high- and low-density high-frequency words. Vowel duration did not differ as a function of neighborhood density. Thus, the observed differences in vowel-space expansion between high- and low-density words cannot be attributed to differences in vowel duration. A small but significant effect of word frequency on vowel duration was found; however, correlations between average vowel duration and average vowel-space expansion were not significant, suggesting that the word-frequency effect was not attributable merely to vowel duration.

The apparent effect of neighborhood density on vowel duration seen in Experiment 1 was not replicated in Experiment 2. Vowel durations in Experiment 2 were in the expected direction (C. Wright, 1979), with longer vowels associated with lower frequency words. No influence of neighborhood density on vowel duration was found. Thus, differences in vowel expansion as a function of word frequency are potentially related to the effect of vowel duration. Differences in vowel expansion related to neighborhood density, however, cannot be attributed to differences in vowel duration.

The finding that both word frequency and neighborhood density influence vowel-space expansion suggests that the differences in vowel-space expansion seen between lexically easy words and lexically difficult words in Experiment 1 were not due to the influence of either word frequency or phonological neighborhood density. Rather, they reflected the combined influence of both neighborhood density and word frequency. Indeed, the largest difference in expansion noted in Experiment 2 was between the high-frequency, low-density words and the low-frequency, high-density words. These were similar to the two conditions from Experiment 1. Moreover, these are the conditions that show the greatest difference in accuracy and latency in speech-perception experiments (e.g., Luce & Pisoni, 1998).

This is the first known study to document an acoustic difference in vowel-formant frequencies as a function of word frequency. This result complements previous research showing that word frequency influences a variety of phonological behaviors, including ongoing sound changes. In general, it has been found that higher frequency words are more likely to undergo reductive articulatory changes that increase the ease of articulation of a word. For example, Hooper (1976) and Bybee (2000) found an influence of word frequency on the rate of consonant and vowel deletions. The more contracted vowel spaces in the high-frequency words are yet another example of a reductive articulatory change associated with high-frequency words.

General Discussion

The results of the two experiments conducted support the hypothesis that lexical neighborhood density influences speech production. In both experiments, vowels spaces associated with high-density words were more expanded than those associated with low-density words. Furthermore, the effect was found to be present in both high- and low-frequency words. Finally, the effect was shown to be independent of vowel duration. The presence of the effect in each of these experimental manipulations reflects its robustness. Given the findings of Moon and Lindblom (1994), we might have expected a positive correlation between vowel duration and vowel-space expansion. The results of one recent study by Bell et al. (2003), however, suggest that these two variables are not as consistently correlated as previously proposed. Bell et al. examined factors that influence vowel reduction (a measure analogous to vowel-space contraction in the current investigation) and word duration in spontaneous conversational productions of 10 commonly occurring function words. In general, Bell et al. found that vowel duration and vowel reduction were correlated. However, there were some contexts in which they were not. For example, the function words *that*, *I*, *it*, and *you* were longer in disfluent contexts than fluent ones, but there was no effect of surrounding disfluency on vowel reduction. Given these findings, the lack of a correlation between these two measures in the current experiment is less surprising.

There are two potential reasons why neighborhood density and word frequency affected vowel production in Experiments 1 and 2. One explanation is that these are active online modifications made to assist spoken-word recognition. Given that expanded vowel spaces are associated with more easily perceptible speech (Bradlow et al., 1996), it seems reasonable to conclude that the relation between neighborhood density and vowel-space expansion is related to perceptual factors. Indeed, R. Wright's (2004) original interpretation of the influence of neighborhood density on vowel-space expansion was that speakers intentionally modified their articulation of the low-frequency/high-density lexically difficult words to maximize their clarity and, presumably, their ease of perception. That is, speakers appear to have a tacit recognition of the perceptual difficulties that are associated with lexically difficult words, and they attempt to counter this difficulty by modifying their production of them. That interpretation fits well with the results from Experiment 2. In perception studies, low-frequency words are more difficult to perceive than high-frequency words. It seems reasonable, then, to presume that the expanded vowel spaces associated with low-frequency words also reflect the general principle that people would modify their articulation to make words maximally clear and perceptible.

An alternative explanation of R. Wright's (2004) original finding was presented by Pierrehumbert (2002). This explanation posits that the differences are due to differences in the long-term representations of high- and low-density words. Pierrehumbert proposed that representations in memory consist of highly detailed exemplars of words. These representations are built through experiences producing and perceiving words in social communication. This proposal follows from research demonstrating that perceptual knowledge includes information on specific perceptual episodes (e.g., Goldinger, 2000). These exemplars include very specific acoustic detail, such as specific formant frequencies and other talker-specific characteristics. These representations are used both in speech perception and production. In perception, people compare tokens of words that they hear with the collection of exemplars in memory during spoken-word recognition. In production, people select one of the exemplars in memory and use it as an acoustic goal for speech production.

In this framework, the influence of phonological neighborhood density on vowel production may arise indirectly, because of the influence that density has on perception. In an exemplar framework, listeners would only encode an exemplar of a target word if they perceived it to be distinct from other known words. As a consequence, listeners would be unlikely to encode an exemplar of a vowel in a high-density word if it were considerably unlike the exemplars of that word already in memory (i.e., an exemplar that was produced with significant vowel reduction). The consequence of doing so would be to make the entire group of exemplars for that word less distinct than those for a phonetically similar word in the same neighborhood. In contrast, listeners would be more willing to encode an exemplar of a reduced vowel in a low-density word, as there would fewer or no phonetically similar words with which the group of exemplars might be confused. If production were to involve the selection from memory of one of the exemplars associated with a word, as Pierrehumbert (2002) proposed, then this would predict the effects seen in Experiments 1 and 2.

Regardless of the locus of the effects of the vowel duration and expansion found in these experiments, they underscore the importance of carefully controlling stimulus characteristics in studies that examine the influence of lexical competition on speech perception. The effects of vowel duration and expansion on speech intelligibility have been well established (e.g., Bradlow et al., 1996). It would be predicted, then, that the more expanded vowel spaces associated with the lexically difficult words would facilitate their perception. Research has shown, however, that these words are perceived less accurately than lexically easy words (e.g., Luce & Pisoni, 1998). Future research should consider whether the increased vowel-space expansion in lexically difficult words decreases the effect of lexical competition. Moreover, future research should examine whether the influence of neighborhood density on articulation extends to other realms. Ultimately, future research should utilize a range of experimental paradigms to examine whether neighborhood-density effects in production are due to active attempts to maximize speech clarity or are the consequence of selective encoding of clearly produced exemplars of high-density words.

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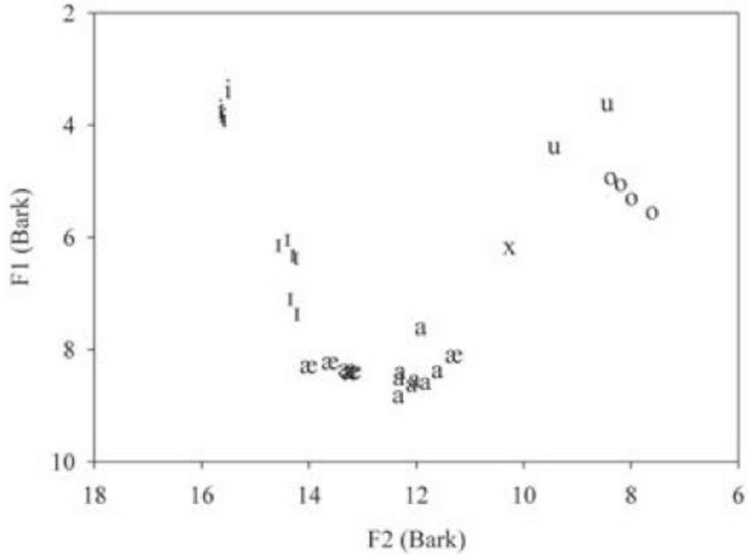

Figure 1.
F1/F2 values (bark) for vowels in lexically difficult words produced by Participant F01 in Experiment 1.

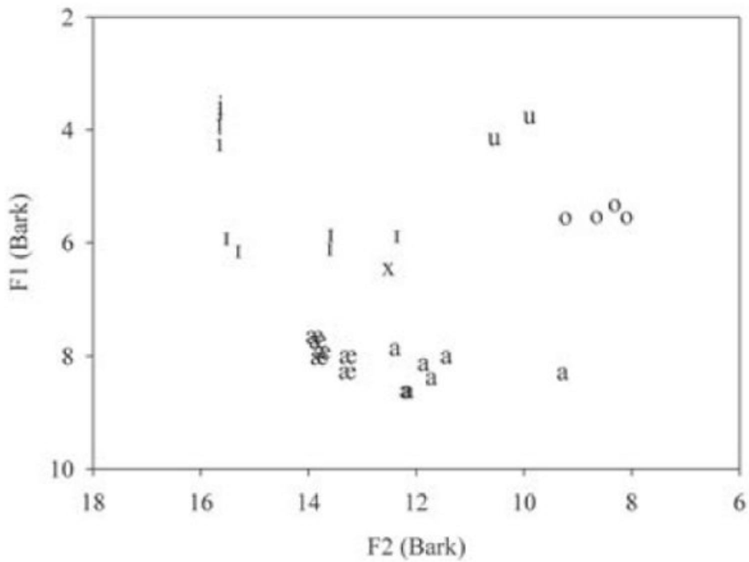

Figure 2.
F1/F2 values (bark) for vowels in lexically easy words produced by Participant F01 in Experiment 1.

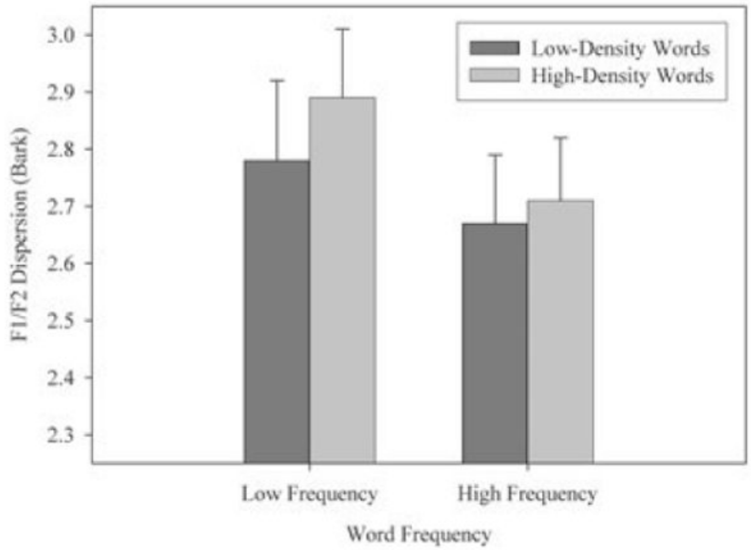

Figure 3.
Mean F1/F2 expansion (bark) of vowels (±SEM) in high-density and low-density high- and low-frequency words in Experiment 2.

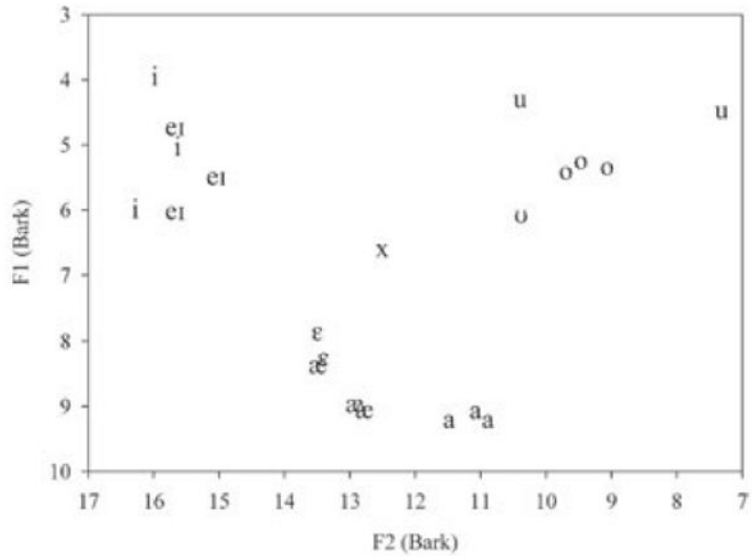

Figure 4.
F1/F2 values (bark) for vowels in low-frequency, high-density words produced by Participant M2 in Experiment 2.

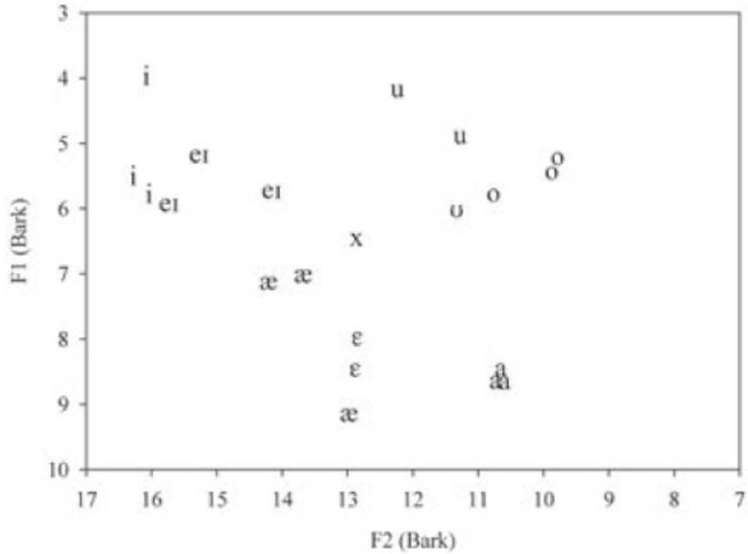

Figure 5.
F1/F2 values (bark) for vowels in high-frequency, low-density words produced by Participant M2 in Experiment 2.

Table 1

Stimulus words for Experiment 1.

Vowel	Lexically easy	Lexically difficult
a	job	cod
a	shop	cot
a	wash	knob
a	watch	wad
æ	gas	hack
æ	jack	hash
æ	path	pat
ɪ	give	hick
ɪ	ship	kin
ɪ	thing	kit
i	peace	bead
i	teeth	weed
o	both	goat
o	vote	moat
u	food	hoop

Table 2

Stimulus words for Experiment 2.

Vowel	High frequency/high density	High frequency/low density	Low frequency/high density	Low frequency/low density
a	got	dock	dot	mop
a	lock	rock	knock	sock
a	pot	top	cot	cop
æ	bad	bag	dad	dab
æ	sad	sang	fad	sag
æ	half	laugh	mash	rash
ε	get	death	debt	deaf
ε	bet	check	pet	pep
eɪ	save	gave	cage	bathe
eɪ	game	gain	dame	babe
eɪ	tape	shape	cake	nape
i	beat	beach	beak	leach
i	team	scene	keen	siege
i	mean	beam	bean	gene
oʊ	note	wrote	moat	rope
oʊ	rose	known	moan	robe
oʊ	bone	loan	roam	dome
u	youth	suit	boot	hoot
u	moon	room	womb	tune
ʊ	foot	put	hook	hoof