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Coarticulation and the Structure of the Lexicon

A dissertation submitted in partial satisfaction of the

requirements for the degree of Doctor of Philosophy

in Linguistics

by

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ABSTRACT OF THE DISSERTATION

Coarticulation and the Structure of the Lexicon

by

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The experiments in this dissertation reveal a previously unknown relationship between lexical confusability and degree of coarticulation. Two confusability categories, defined by relative frequency (*R*), were investigated: low-*R* (or "hard") words have frequencies that are low relative to the summed frequencies of their phonological neighbors; high-*R* (or "easy") words have frequencies that are high relative to the summed frequencies of their phonological neighbors. Phonetic measures of coarticulation show that the *more confusable* (low-*R*) words exhibit *more* coarticulation than the less-confusable (high-*R*) words. This general finding holds across two types of coarticulation (nasal coarticulation and vowel-to-vowel coarticulation), across both directions of coarticulation (anticipatory and carryover), and across two languages

(English and French). Further investigation indicates that the effect of confusability on coarticulation (i) arises at the level of whole words and (ii) is not sensitive to phonological contrast. Low-*R* words show greater coarticulation regardless of whether the coarticulatory source and/or target segments give rise to the phonological confusability. English and French both show the effect of *R* on nasal coarticulation, despite the fact that nasal vowels are contrastive in French but not in English. Comparison of the confusability effect on coarticulation with previous findings of hyperarticulation supports a functional theory in which talkers use increased coarticulation and/or hyperarticulation to mitigate listeners' lexical access difficulties. This interpretation suggests that coarticulation should be viewed as a perceptually useful source of linguistic information, providing cues that can be efficiently used by listeners to facilitate lexical perception.

Chapter 1: Introduction

Coarticulation, or the acoustic and articulatory variability that arises when the articulations of neighboring segments overlap, is a fundamental part of language sound systems. It is an important source of patterned variation in speech, explaining how segmental context systematically effects different phonetic realizations of a single phonological category. As such, it is also a probable basis for certain instances of phonological sound change (e.g., Ohala, 1993). And coarticulation is also probably the most important feature of connected speech. In fact, it is ubiquitous in real speech, allowing for dynamic transitions between adjacent segments (both within and across words) and making speaking perhaps easier or even possible at all for a talker. But it is also one of the main processes associated with higher-level connected speech factors like information structure, speech style, and communicative situation. And coarticulation is extremely pervasive cross-linguistically. There has been no discovered case of a language in which some type or degree of coarticulation could not be found, leading it to be taken as a universal phenomenon (Farnetani, 1999). But even though it is pervasive, it is also significant as a source of cross-language variation, with different languages showing different patterns and degrees of various types of coarticulation.

Despite its fundamental status in speech production and the extensive and rigorous body of research investigating it, however, there is still no consensus on such elemental theoretical issues as the origin, function, and control of coarticulation (see

Farnetani, (1999) for further discussion). The range of views arises in part from the fact that this patterned variation is itself variable, and the remaining variability has been considered by different researchers with attention to different potential factors—intrinsic segmental properties, cross-language variation, communicative context—and different consequences—notably, the problem of representational invariance. Eventually, a comprehensive theory of coarticulation, along with an appropriate theory of lexical representation, must of course be able to account for all of the coarticulatory variation and variability found in speech data.

In this dissertation, I investigate another factor or set of factors that I show to play a role in constraining coarticulation: factors imposed by the structure of the lexicon. These are factors that emerge from various statistics of the lexicon: perhaps most obviously *lexical frequency*, which simply refers to the frequency with which individual lexical items occur in a language, but also phonological *neighborhood density*, or the number of lexical items that are phonologically similar to a target word. (A lexical neighborhood is simply a group of lexical items that are similar to one another in some way, which might be semantic or phonological or even orthographic, but here we will be concerned just with phonological neighborhoods.) These statistics allow us to describe or characterize certain aspects of the lexicon as a whole, but also, through the effects they have, to predict certain facts about individual items *in* the lexicon—both facts about production and facts about perception. Importantly for the current study, these factors have been shown to affect phenomena related to coarticulation, namely different types of reduction, and to account for some word-specific variability. The effects of lexical factors on coarticulation are of additional interest because of the emerging importance of lexical statistics in models of word perception and speech production, as well as in theories of lexical representation.

1.1. Lexical Effects

1.1.1. Lexical effects on speech production

It has been well established that the structure of the lexicon influences speech production. The effects that lexical frequency might have have been much discussed in the literature (Balota, Boland, & Shields, 1989; Zipf, 1935; Bybee, 2001; Pierrehumbert, 2002), often with the prediction that highly frequent words will be more subject to reduction processes. Indeed, high frequency words are empirically more likely to be reduced than low frequency words, showing durational shortening, vowel reduction, and final segment deletion in both experimental studies (e.g., Fidelholz, 1975; Munson & Solomon, 2004) and corpus studies (Jurafsky, et al., 2001; Jurafsky, et al., 2000). Additionally, low frequency words have been shown to be more susceptible to phonological speech errors than high frequency words (Dell, 1990; Stemberger & McWhinney, 1986).

Lexical neighborhood density has also been shown to have effects similar to those for frequency. Wright (1997, 2004), for instance, found that “easy” words, roughly those from sparse neighborhoods (with mainly low frequency neighbors), are produced with consistently greater vowel reduction (measured as centralization in the vowel space) than “hard” words. (This finding was replicated by Munson & Solomon (2004) using a straightforward (i.e., non-frequency-weighted) measure of neighborhood density.) And Goldinger and Summers (1989) showed that the VOT difference in the initial stops of voiced-voiceless minimal pairs (e.g., *touch – dutch*) is greater for pairs of words from dense neighborhoods than for those from sparse neighborhoods. Further effects of lexical neighborhood on speech production are reported by Vitevitch (1997), who elicited fewer errors for words with many similar sounding neighbors than for words with few neighbors. And Vitevitch (2002a) showed that speakers name equally familiar pictures more quickly and accurately when the picture name is from a dense neighborhood than when it is from a sparse neighborhood. This effect persists even when positional segmental probability and biphone probability are controlled (indicating that these differences cannot be attributed to differences in the difficulty of articulatory planning, at least these levels).

1.1.2. Lexical effects on word recognition

It has been shown that lexical factors play a role in predicting a word's intelligibility in lexical recognition as well. A number of psycholinguistic studies have investigated the effect of lexical factors like usage frequency and phonological similarity neighborhood on lexical access in word recognition. A processing advantage for high frequency words, for example, has been often cited (e.g., Howes, 1957; Gordon, 1983; Glanzer and Eisenreich, 1979; Segui, et al., 1982), suggesting that more frequently occurring words are more easily recognized or accessed than less common ones. Other studies have shown that the effects of frequency on intelligibility are mediated by the number of neighbor words for a given word (e.g., Luce, 1986; Pisoni, Nusbaum, Luce, &

Slowiaczek, 1985; Havens & Foote, 1963; Hood & Poole, 1980; also Harley & Bown, 1998; Vitevitch, 1997).

All other things being equal, words with many close neighbors (i.e., those from dense lexical neighborhoods) are recognized less quickly and less accurately than those with few neighbors in several types of experimental tasks (Luce, 1986; Goldinger, Luce, & Pisoni, 1989; Vitevitch & Luce, 1998). Furthermore, the disadvantageous effect of dense neighborhoods is compounded by the presence of high frequency neighbors (Luce, 1986). Therefore, a word's speaker-independent intelligibility seems to derive from the statistical likelihood that it will be chosen from among other possible words, depending on both lexical frequency and the set of similar, competing words, the neighbors (Luce, 1986).

Current models of spoken-word recognition agree that lexical access involves discriminating among various entries in the mental lexicon. An acoustic-phonetic input activates multiple phonologically-related lexical representations that compete. The difficulty of accessing a particular lexical item, then, is relative to the probability of correctly recognizing a target word from among its lexical neighbors, and can be thought of in terms of the activation of a target word relative to the activation of its competitors (Luce & Pisoni, 1998; Norris, McQueen, & Cutler, 2000; Marslen-Wilson & Zwitserlood, 1989). There are many factors that contribute to the relative activation of a word, particularly in a communicative context, but we have seen evidence that the frequency of a word and the number and frequencies of phonologically similar competitors at least are among them.

The Neighborhood Activation Model of spoken-word recognition (NAM) developed by Luce and colleagues (Luce, 1986; Luce & Pisoni, 1998) takes into account both of these factors, representing the relative degree of activation by a frequency-weighted ratio of a word to its neighbors. This relative frequency ratio (referred to in this dissertation as *R*) can be estimated as the frequency of a word divided by the sum of the frequencies of all of its neighbors. (Luce (1986) investigated similar ratios which took additional factors such as segmental confusion into account in the weighting, but ultimately, he determined that this simpler ratio was predictively sufficient.) Words with high relative frequencies (at the extreme, those with a high frequency and few and infrequent neighbors) receive relatively little competition from their neighbors, so lexical access for these words is relatively easy (i.e., they are not very lexically confusable). On the other hand, words with low relative frequencies (those with a low frequency and many frequent neighbors) receive much more competition from their neighbors, and so lexical access for these words is relatively more difficult (i.e., they are lexically confusable).

Figure 1 illustrates high and low relative frequencies, showing target words (represented by the dark bars) surrounded by their neighbors (represented by the light bars). In the high-*R* picture, the target word stands out, while in the low-*R* picture, the target word is obscured by its neighbors, reflecting relative difficulty in lexical access. With respect to intelligibility, then, words with a high relative frequency (high-*R* words) may be referred to as “easy” and those with a low relative frequency (low-*R*), as “hard” (Luce, 1986; Pisoni, Nusbaum, Luce, & Slowiaczek, 1985; Wright 1997).

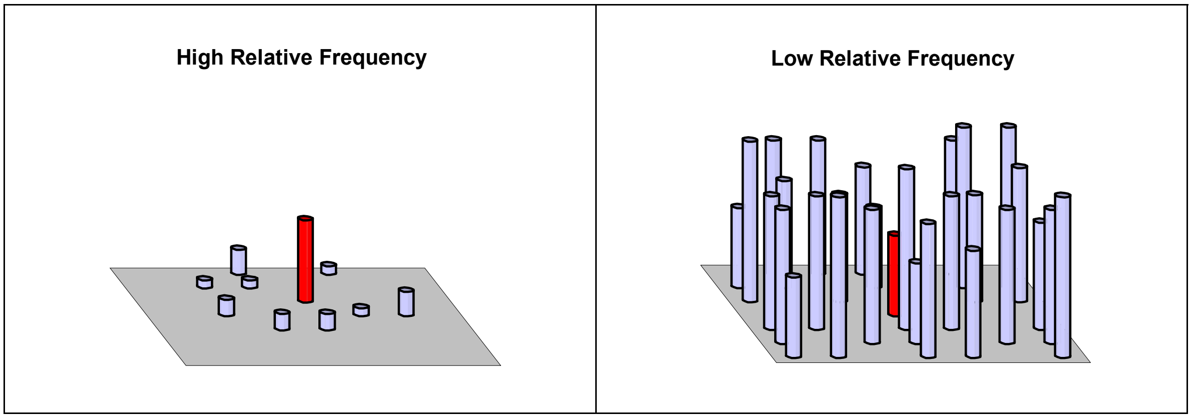

Figure 1 Schematic Illustration of High vs. Low Relative Frequency. Target words are represented by dark bars, neighbors by light bars; frequency is represented by bar height.

1.1.3. Relation between lexical effects on production and perception

What is the relevance of a discussion of lexical effects on perception in a study on production? In fact, the effects of lexical factors on production have been interpreted by a number of researchers as being motivated by their effects on intelligibility (e.g., Wright, 1997; Brown, 2001; Billerey, 2000; Gregory, 2001). And even interpretations that do not rely on direct motivation by the perceptual effects suggest that the two types of effects arise from the same process of lexical access (e.g., Jurafsky, et al., 2002; Pierrehumbert, 2002).

1.1.3.1. Functional Relation: Speaker-Listener Communicative Interactions

Lindblom characterizes speech production as a dynamic balance regulated by communicative context between the competing forces of a speaker's desire to be understood, on the one hand, and his desire to minimize articulatory effort, on the other. A speaker must produce a signal from which his listener can recover the intended message. If he is not sufficiently careful, communication will be unsuccessful. But as long as a speaker remains intelligible to his listener, there is no reason that he cannot adjust his production to reduce the amount of effort he must expend as speaker. So the speaker has to monitor the communicative situation, and as factors exist that place extra demands on the listener, decreasing his chances of recovering the message, the speaker must adjust his pronunciation in order to produce clearer speech (referred to in Lindblom's model as "hyper-speech"). However, when conditions are favorable for communication, the speaker is free to conserve articulatory effort, producing reduced speech (or "hypo-speech").

Research has shown that speakers are sensitive to a number of different types of listener difficulties and make corresponding acoustic-phonetic accommodations. For instance, people talk more loudly and slowly in noisy environments than in quiet ones (Lombard, 1911; Lane and Tranel, 1971; Hanley and Steer, 1949). Likewise, speech directed toward hearing-impaired listeners has a decreased rate (achieved both by pauses between words and by increased durations of individual segments) and a lesser degree of phonological reduction (e.g., fewer reduced vowels and fewer unreleased word-final stops) relative to normal conversational speech (Picheny, Durlach, and Braida, 1986). Factors internal to the structure of an interaction may also motivate speaker accommodations. Lieberman (1963), for example, demonstrated that words that are less predictable from their conversational context are more intelligible when removed from their context and presented in isolation than are more predictable words, suggesting that less predictable words are more clearly pronounced in some manner. Similarly, the second occurrence of a word in a narrative shows a decrease in vowel duration relative to the first occurrence of the same word, rendering the second occurrence less intelligible than the first (Fowler and Housum, 1987). The authors suggest that new information, mentioned for the first time in a conversation or narrative, is spoken more clearly than old information because (as with the less predictable words in the Lieberman study) listeners will be unable to rely on inferences from context to provide top-down cues to aid them in lexical perception.

If lexical factors affect a word's intelligibility, increasing or decreasing the probability of a listener correctly identifying a word, then these factors might be predicted to affect communication like 'noise' that both listeners and speakers have to accommodate. So speakers, for their part, should produce "hard", or lexically confusable, words more carefully than "easy" ones in order to increase the likelihood that even the most confusable words they say will be understood.

Wright (1997, 2004) interpreted his result within this framework, asserting that speakers produce more dispersed vowels in "hard" words with the explicit purpose of making these words easier to perceive. An expanded vowel space makes vowels more distinct from one another and therefore less likely to be confused. And in fact, an expanded vowel space is one property of the speech of more intelligible talkers (Bradlow, et al., 1996). In this way, then, speakers compensate, at least to some degree, for the increased difficulty listeners may have due to the lexical confusability of the word being spoken and perceived. (It must be noted, though, that the accommodations speakers make do not fully eliminate the difference in difficulty between easy and hard words; Bradlow and Pisoni (1998), for instance, showed that the hyperarticulated hard words examined in Wright's (1997) study were still less intelligible than easy words.)

1.1.3.2. Mechanistic Relation: Lexical Access as the Mechanism

The effects on production might also arise in part due to the same sorts of facilitative and inhibitory influences on word activation in lexical retrieval that we have seen affect lexical recognition (Jurafsky, et al., 2001; Vitevitch, 2002a; Pierrehumbert, 2002). As low frequency and high neighborhood density slow word recognition in lexical perception, it stands to reason that these factors might also slow lexeme retrieval in production. In fact, in picture naming tasks, objects with low frequency names take longer to name than objects with higher frequency names (Oldfield & Wingfield, 1965; Jescheniak & Levelt, 1994). This timing lag might then cause on-line adjustments in pronunciation, an explanation Jurafsky[1] invokes to explain the hyperarticulation (or lack of reduction) in low frequency words. Empirical work on vowel production in the vicinity of disfluent speech reinforces this idea, showing that words surrounding disfluencies tend to be hyperarticulated (Bell, et al., 2003). The Bell, et al. study provides evidence that planning difficulties can lead directly to online adjustments in articulation. (An alternate explanation for the effect of difficulty in lexical retrieval on fluent speech is that a speaker's own difficulty does not directly condition the adjustments, but rather it is a signal to him that the listener is likely to have difficulties that he should try to compensate for in his production.)

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[1] Pierrehumbert (2002) attributes this view to Jurafsky (2002), though it is possible that this view was more directly stated in the oral version of the paper (Lab Phon VII).

However, with respect to neighborhood density, words with denser neighborhoods receive more activation (from more phonological neighbors) in the normal course of perceiving and producing words, giving them higher resting activation levels that render them in fact more quickly and accurately retrieved from the lexicon than words with sparse neighborhoods. Recall that in a picture naming task in which neighborhood density was the variable, speakers had shorter response latencies for objects with high density names (Vitevitch, 2002a). And words from high density neighborhoods are also less likely to exhibit speech errors (Vitevitch, 1997). So the effects of neighborhood density on lexical access are different for non-auditory lexical access (for speakers) and spoken word recognition (for perceivers). But the factor still influences speech production as well as perception. Therefore, although there is a mechanistic relation between the production effects and lexical access, the precise consequences of this relation are hard to predict. Since *low* frequency and *low* neighborhood density have the same effect of making lexical access more difficult for a talker during speech production, the same direct or automatic effect in production should be predicted. But in fact, it is the production of *low* frequency words and *high* density words that pattern together. And aside from the hint we get from the disfluent speech data, it is not obvious what particular adjustments difficulty in lexical access should lead to.

1.2. Coarticulation and Lexical Effects

1.2.1. Coarticulation and Reduction

Wright (1997, 2004) demonstrated that lexical factors affect reduction, with lexically confusable words showing *less* reduction (i.e., greater hyperarticulation) than more confusable words. Given the close relationship between reduction/hyperarticulation and coarticulation in most theories of coarticulation, a prediction for the relation between lexical factors and coarticulation should fall out from the facts on reduction. However, what the nature of the relation between the reduction/hyperarticulation phenomenon and coarticulation should be is not, in fact, immediately clear.

On one view, coarticulation is a type of reduction. It is manifested as a reduced displacement (an 'undershooting' of the abstract acoustic target for a segment) and a shift of movements towards the surrounding context, and it is driven by the desire for increased ease of articulation (Lindblom, 1990; Moon & Lindblom, 1994). In effect, coarticulation is the result of articulatory laziness or sloppiness in the same way that a reduced vowel might be thought of as a sloppier version of its unreduced, carefully-produced counterpart. This minimization of effort is counteracted only when the communicative situation places extra demands on the listener, pushing the speaker to produce clearer speech (hyperspeech) in order to maintain intelligibility. So cases in which a speaker would suppress reduction or hyperarticulate, as in hard words, are also cases in which it would be expected that coarticulation would be reduced, yielding more extreme, canonical, careful vowels.

However, this prediction does not derive naturally from a coproduction theory of coarticulation (e.g., Fowler, 1980, 1985; Bell-Berti & Harris, 1981) or the closely related model of gestural phonology (Browman & Goldstein, 1992). In both theories, coarticulation is not an explicit adjustment of a gesture; rather, it is simply the temporal and spatial overlap of gestures which have their own intrinsic spatial and temporal structure. (The overlap of gestures may indeed result in reduced movements, but this is not the essential nature of coarticulation.) Reduction, on the other hand, is represented as a decrease in the amplitude or size of a gesture, often accompanied in connected speech by an adjustment in the overall duration of series of gestures, while hyperarticulation can be represented as an increase in the size of a gesture. If the amplitude of a gesture is increased without increasing the overall time of articulation, there will be greater overlap of adjacent gestures, resulting in greater coarticulation. In fact, in order for hyperarticulation *not* to lead to greater coarticulation (as in the first hypothesis), it would be necessary for articulatory movements to be not only more extreme, but also faster. The two hypothetical cases are illustrated in Figure 2.

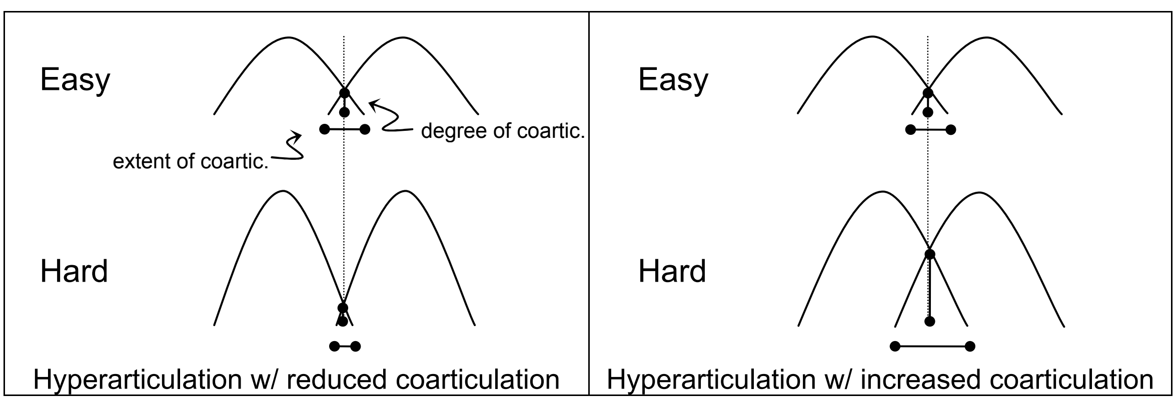

Figure 2 Two competing predictions about the relation between hyperarticulation and coarticulation. The picture on the left shows hyperarticulation in the hard condition with *reduced* coarticulation. The picture on the right shows hyperarticulation in the hard condition with *increased* coarticulation.

1.2.2. Word Intelligibility and coarticulation

We could also make a prediction about lexical effects on coarticulation based on their effects on word intelligibility. If lexical factors influence production *through* perceptual effects, then what is the relation between word intelligibility and coarticulation? Again, we could imagine two completely opposite hypotheses, depending on the view we take of coarticulation. In perhaps the more popularly cited view, coarticulation is thought to result from a move toward ease of articulation, and it yields less distinct segments that are perhaps less extreme and overlapped (e.g., Moon & Lindblom, 1994). Basically, it is variability that has to be factored out by listeners. And if coarticulation is hard for listeners, speakers should produce less of it in confusable words that are already harder for listeners. This seems to accord with certain findings in the traditional clear speech literature, which show less CV coarticulation in speech produced in a careful manner than in normal spontaneous speech (e.g., Duez, 1992; Krull, 1989). But on the other hand, the amount of acoustic information contained in a coarticulated speech signal may not actually be reduced. Rather, it is rearranged temporally. We could think of the overlapping of segments as actually usefully spreading acoustic cues throughout a greater extent of the speech signal. In the overlapped regions, then, information about both segments are being transmitted very efficiently in parallel (Mattingly, 1981). If this is the scenario, and coarticulation can help in lexical perception, then speakers should produce more coarticulation in the more confusable words.

1.2.3. Brown, 2001

In an earlier study (Brown, 2001), I began my investigation of lexical effects on coarticulation with two experiments: a production experiment and a lexical decision perception experiment. In the production experiment, speakers produced high-*R* and low-*R* words with an environment for either anticipatory nasal coarticulation or carryover vowel-to-vowel coarticulation, and analysis of the data revealed that speakers produced *more* of both types of coarticulation in the low-*R* (hard) words. With respect to nasal coarticulation, vowels were more nasal in low-*R* words, and with respect to vowel-to-vowel coarticulation, vowels in low-*R* words showed greater contextual deviation from canonical on the F1 (vowel height) dimension. (I will discuss these vowel-to-vowel results further in section 3.4.2, expressing some slight reservations.) Assuming that the effect was communicatively functional, the perception experiment investigated what effect this increase in coarticulation would have on a listener trying to perceive lexically hard words. Listeners made timed lexical decisions on audio versions of the same words, spliced so that half contained the usual coarticulation and half contained none. And in fact, listeners responded to words *with* coarticulation faster than to those without.

1.3. Current Study

Taking these findings as a starting point, the current study substantially extends the research on the relation between coarticulation and the lexicon. It will be demonstrated and reconfirmed through analysis of a much expanded corpus that coarticulation *is* influenced, or constrained, by lexical factors, with a focus on providing a clear description of the ways coarticulation is affected. In particular, it will be shown that coarticulation is predictively related to a measure of lexical confusability that incorporates frequency and neighborhood density, and that there is *more* coarticulation in more lexically confusable words. This effect is robust, seen across types and directions of coarticulation and across data from both English and French.

The study then addresses other factors, one supralexical and one sublexical, that might modify the lexical effect by contributing to a more specific type of confusability. First, the possible effect of phonological contrasts is investigated by comparing nasal coarticulation data in French (where vowel nasalization is contrastive) to that in English, and also across vowel groups differing in nasal contrastiveness within French. Then, the possible effect of specific instances of potential confusion within a neighborhood is investigated by comparing the lexical effect in words in which the coarticulating segment is the locus of potential confusion with another word in the neighborhood and in words in which it is not. The data do not reveal that the effect on coarticulation is constrained by either type of factor. Thus, the results are consistent with a theory in which the effect is related directly to the statistics of the lexicon and reinforce the view of the effect as robust and general.

The data presented in this dissertation are basic to an understanding of both coarticulation and influences of the lexicon. They reveal another set of factors that condition coarticulatory variability. And they also reveal another type of word-specific pattern that is conditioned by lexical factors. And the link between these two fundamental areas of linguistic study is additionally interesting in light of the place each of these areas holds in broadly functionalist discussions of communication—of interactions between talkers and listeners. Finally, a functional interpretation of this data will be proposed and evaluated in which talkers, perhaps somewhat surprisingly, use *increased* coarticulation to mitigate difficulties for the listener that result from the structure of the lexicon.

1.4. Outline of the Dissertation

The remainder of this dissertation is organized as follows:

Chapter 2 describes the experimental methods. First, it discusses the calculation of the various lexical statistics that will be used in the study. It then describes the design of the main English and French corpora. And it addresses the data acquisition procedures and measurement techniques.

Chapter 3 reports the main results from the English corpus. The findings address the effect of lexical confusability on the production of nasal and vowel-to-vowel coarticulation in English. Questions about the extent and directionality of the effect are addressed. And the relation between the effect of lexical factors on coarticulation and those on reduction are also discussed.

Chapter 4 reports the main results from the French corpus. The findings address the effects of lexical confusability on the production of nasal coarticulation in French, demonstrating cross-linguistic generality of the effects. Importantly, the results also address the question of whether and how phonological organization interacts with lexical effects (both within and across languages). Specifically, they show that the way the particular set of phonological contrasts in a language constrains the influence of lexical factors on coarticulation is limited.

Chapter 5 reports on additional analyses of a subset of the English nasal coarticulation corpus. The analyses investigate what factors in the lexicon play a role in lexical confusability. Specifically, they bear on whether the effect of lexical factors on coarticulation is really *lexical*, operating at the whole-word level, or whether the confusability that leads to a coarticulation effect is actually sublexical, referring to confusability by particular individual segments.

Chapter 6 summarizes the results presented in this dissertation, evaluates a functional interpretation of the findings, and provides an overall discussion about lexical effects on coarticulation.

Chapter 2: Methods

A study involving a series of production experiments was carried out to address the questions posed in Chapter 1. Understanding the nature of the effect of the lexical factors on coarticulation and the factors that contribute to it requires the analysis of a substantial and carefully designed and collected speech corpus. The corpus for the current study includes English words exemplifying two types of coarticulation and various lexical properties produced by American English speakers. The specific properties of this corpus and the ways in which these properties allow us to address the questions posed in this dissertation will be described in detail below. A secondary corpus of French speech allows for a comparison of the effect in two languages and investigates the role of phonology in mediating the effect. French was an especially appropriate choice for an investigation of the interaction of phonological contrastiveness with the effects of lexical contrastiveness (or lexical confusability) since certain vowels in French contrast (at least categorically) with respect to nasalization (/ɛ/-/ɛ̃/, /ɔ/-/ɔ̃/, /ɑ/-/ɑ̃/, /œ/-/œ̃/—i.e., they are "nasal-contrastive"), while other vowels in French have no contrasting nasal counterpart: /i/, /y/, /u/, which are "non-contrastive". The design of the corpus permits a further experiment which addresses the issue of what properties of the structure of the lexicon influence these sorts of effects.

All of the data collected for the study corpora were acoustic. Although articulatory and kinematic data have proven to be very useful for the study of subtle phonetic phenomena, and for the study of coarticulation in particular, the collection of such data was impractical for the current study for two reasons. First, it generally requires some apparatus that is uncomfortable or at least unnatural for speakers and that therefore draws the speakers' attention to the act of articulating. Because the current study investigates a phenomenon that may crucially depend on the naturalness of the speech situation (the lexically-mediated adjustments may be a property of *listener-directed* speech), it was important that the speech be in a style that is as natural as possible. Second, because the effect of interest is one whose motivation may be perceptual in nature, it is more directly relevant to look at the acoustic results of coarticulation rather than its articulatory source. Therefore, data collection for the study corpora involved making audio recordings that were analyzed acoustically. And because natural, listener-directed speech was desired, for the main corpus, speakers were recorded in the presence of a listener naïve to the purpose of the study (Brown, 2001).

2.1. Main Study Corpus: English

2.1.1. Speech Materials

The corpus included 205 monosyllabic and disyllabic words. Among the monosyllabic words were both nasal coarticulation test words (exemplifying anticipatory and carryover nasal coarticulation) and canonical vowel control words. The disyllabic words were all vowel-to-vowel coarticulation test words (again exemplifying coarticulation in both directions).

2.1.1.1. Lexical Properties

Within each set of test words, there were two groups of words: one group of "easy" words with few lexical neighbors and high usage frequencies relative to those neighbors, and one group of "hard" words with many neighbors and low relative frequencies. All words were listed in the CELEX Lexical Database, which is a corpus of 52,446 lemma entries and 160,594 wordforms taken from 17.9 million words of text and spoken dialog (Baayen, Piepenbrock, & Gulikers, 1995). CELEX also provides phonetic transcriptions of all entries, which, for the purpose of this study, were adjusted to represent a general California dialect of American English rather than British pronunciation. Both the sets of neighbors and the lexical frequencies of test words and neighbors were determined from this corpus.

Phonological similarity neighborhoods were modeled crudely on a phonemic basis. Neighbors, for the purposes of this study, were determined using the single phoneme addition, subtraction, or substitution method (Greenberg and Jenkins, 1964; see also e.g., Luce, 1986; Wright, 2004; Munson, 2004), where all words differing from the target word by a single phoneme are considered to be neighbors of that word. The neighborhood of the word *pan*, for example, includes *ban, can, fan, pad, pack, pass, pen, pain, span, pant, plan,* and *Ann*, but not *plant, past,* or *spank*.

To take into account both the frequency of the target word and the properties of its lexical neighbors, relative frequency (*R)* was calculated by dividing the log frequency of the token word by the sum of the log frequencies of the word and all of its neighbors:

$$R = \frac{\text{logfreq}_{\text{wd}}}{\text{logfreq}_{\text{wd}} + \sum_{i=1}^{n} \text{logfreq}_{\text{n}}}$$

The log base-10 transformations were calculated in order to improve the linearity of the distribution of frequencies.

Words were selected for inclusion in the study on the basis of having *R* values at the upper or lower end of the range of *R* values for words of the same type. The words with high *R* values were called "high-*R*" and were comparable to "easy" words in similar studies, and the words with low values for *R* were called "low-*R*", comparable to "hard" words. Absolute log frequency means and distributions were balanced across the two relative frequency conditions for each type of coarticulation. Furthermore, all selected words were highly familiar, with a familiarity rating of 6.0-7.0 on the 7-point Hoosier Mental Lexicon scale (Nusbaum, Pisoni, & Davis, 1984; this is the familiarity range used by Luce & Pisoni (1998)).

2.1.1.2. Nasal Coarticulation Test Words

Nasal coarticulation test words were of two types: monosyllabic words with a nasal consonant in the syllable coda, or words of the form C_0CVN(C), and monosyllabic words with a nasal in the syllable onset, or words of the form (s)NVCC_0 (where C_0 indicates zero or more non-nasal consonants and N is any nasal consonant). The nasal coda words, hereafter referred to simply as CVNs, are intended to exhibit anticipatory coarticulation of the nasal on the preceding vowel, and the nasal onset words, referred to as NVCs, are expected to show carryover coarticulation of the nasal onto the following vowel (as schematized in Figure 3).

C_0 C **V** N (C)   (s) N **V** C C_0

Figure 3 Anticipatory (left) and carryover (right) nasal coarticulation

There are 48 CVNs and 40 NVCs, with half of the words in each group being high-*R* (“easy”) and half being low-*R* (“hard”). Vowel quality was balanced across hard and easy groups and, to the extent possible, across anticipatory and carryover groups. High vowels were avoided to permit consistent nasality measurements to be made, as described in section 2.1.4.1 below. The identity of the nasal consonant (/n/, /m/, or /ŋ/) was also balanced across lexical confusability groups. Since the nasals occurred in both simple and complex onsets and codas, the number of complex codas in CVNs and the number of complex onsets in NVCs were balanced to the extent possible across lexical conditions; however, neither could be perfectly balanced. Words with simple nasal onsets or codas are almost all from large neighborhoods, so they tend to have uniformly low relative frequencies. In order to find nasal words with smaller neighborhoods and higher relative frequencies, words with complex nasal onsets and codas had to be tapped as well. However, since neighbors are defined by one phoneme addition, deletion, or substitution (meaning that one segment in the onset or coda had to remain unchanged), these words all had small enough neighborhoods that nearly all had high relative frequencies. Therefore, as many low-*R* complex onset/coda words and as many high-*R* simple onset/coda words as possible were chosen, and the rest of the word sets were filled out by balancing just the vowel, nasal, and lexical factors. Figure 4 schematizes the range of nasal word types.

$$\mathrm{C}\left\{\begin{array}{l}\text{/ɛ/, /æ/, /ɑ/,}\\ \text{/Λ/, /aʊ, o/,}\\ \text{/aɪ, eɪ/}\end{array}\right\}\mathrm{N\ (C)}$$

$$\mathrm{(S)\ N}\left\{\begin{array}{l}\text{/ɛ/, /æ/, /ɑ/,}\\ \text{/Λ/, /aʊ, o/,}\\ \text{/aɪ, eɪ/}\end{array}\right\}\mathrm{C}$$

Figure 4 CVN and NVC word types included in the study corpus

As stated previously, absolute log frequency was balanced across lexical confusability groups for each type of coarticulation. Log frequency and *R* were also balanced across the two coarticulation groups (anticipatory and carryover nasal coarticulation). The mean log frequency and the mean and range of *R* values for words in each nasal coarticulation category are listed in Table 1. The set of CVNs controlled and balanced additional lexical and neighborhood properties as well, as described in Chapter 5 below. All CVN and NVC test words are listed in Appendix 1 with their log frequencies, neighborhood densities, and relative frequencies.

	CVN			NVC		
	log freq.	*R*	*R* range	log freq.	*R*	*R* range
Low-*R*	2.31	.061	.028 - .087	2.56	.050	.026 - .083
High-*R*	2.42	.206	.125 - .328	2.60	.193	.126 - .421

Table 1 Mean Log Frequency, Mean Log Relative Frequency (*R*), and *R* range for nasal coarticulation test words

2.1.1.3. Vowel-to-Vowel Coarticulation Test Words

All vowel-to-vowel coarticulation test words were of the form (C)CV́CV, with first syllable stress. In the V-to-V coarticulation case, as opposed to the nasal case, anticipatory and carryover coarticulation were examined in the same set of words (by looking at the two different vowels). Due to the phonotactics of English, the set of possible vowels for the V2 position is quite limited. Only /i/, /oʊ/, /e/, and /ɔɪ/ can occur unreduced in unstressed open final syllables. And of this limited set, only /i/ and /oʊ/ occur in enough words to permit the selection of a balanced set of stimuli. Words with V2 reduced to schwa could not be included because schwa arguably has no independent vowel quality to induce anticipatory coarticulation. Additionally, only initial stress words were used because there are relatively few final-stress words in English, so their neighborhoods are always small (assuming neighbors match for stress), making them all high-*R*. There were three groups of CVCV words, then, those ending in /i/, those ending in /o/ (/oʊ/), and a so-called V-matched set in which the set of vowels for V1 and the set of vowels for V2 are identical and balanced so that the same vowels coarticulate with the same other vowels in both the anticipatory and carryover directions. These sets of CVCV words are schematized in Figure 5. The CVC/i/ set was most extensive because CVC/i/s are the most common CVCVs in the lexicon as a whole (excepting schwa-final words), and also because this is the word type that was used in the earlier study (Brown, 2001) and which was known to exhibit an effect of relative frequency (*R*) on coarticulation. In total, there were 60 words: 30 high-*R* words and 30 low-*R* words. Recall that although the CVCV words seem to be grouped by V2 in the Figure, they exemplify anticipatory as well as carryover coarticulation. It is simply the case that for carryover coarticulation, the set of target vowels (V2s) in the test words, reflecting the lexicon of English, is more constrained, while in the case of anticipatory coarticulation, it is the set of influencing vowels that is constrained.

$$\text{(C) C} \left\{ \begin{array}{l} \text{/ɛ/, /æ/, /ɑ/,} \\ \text{/ʌ/, /aʊ, o/,} \\ \text{/u, ʊ/} \end{array} \right\} \text{C /i/}$$

$$\text{(C) C} \left\{ \begin{array}{l} \text{/i, ɪ, ɛ/, /æ/,} \\ \text{/ɑ/, /ʌ/} \end{array} \right\} \text{C /o/}$$

$$\text{(C) C} \left\{ \text{/i, ɪ/, /e/, /o/} \right\} \text{C} \left\{ \text{/i, ɪ/, /e/, /o/} \right\}$$

Figure 5 CVCV words types included in the main study corpus. There are 24 CVC/i/ tokens, 12 CVC/o/ tokens, and 12 V-matched tokens.

Segmental context was balanced across conditions. Importantly, the influencing vowel (the vowel whose coarticulatory effect was being measured) was balanced, at least with respect to vowel height, and usually completely. The place of articulation of the intervocalic consonant was also balanced, as were the number of words with an intervocalic flap. The CVC/i/ words were even more closely balanced across lexical conditions. They were chosen in high-*R*/low-*R* pairs such that each individual low-*R* word had a corresponding high-*R* word in which the vowels (or, again, at least vowel height), the intervocalic C, and log frequency were simultaneously matched.

The mean log frequency and the mean and range of *R* values for words in each V-to-V coarticulation category are listed in Table 2. All CVCV test words are listed in Appendix 2 with their log frequencies, neighborhood densities, and relative frequencies.

	all CVCV			CVC/i/		
	log freq.	*R*	*R* range	log freq.	*R*	*R* range
Low-*R*	1.23	.074	0 - .110	1.38	.067	.036 - .086
High-*R*	1.52	.444	.186 - 1.000	1.43	.348	.186 - 1.000
	CVC/o/			V-matched set		
	log freq.	*R*	*R* range	log freq.	*R*	*R* range
Low-*R*	1.50	.084	.035 - .110	1.21	.067	0 - .107
High-*R*	2.02	.574	.218 - 1.000	1.40	.318	.218 - .386

Table 2 Mean Log Frequency, Mean Log Relative Frequency (*R*), and *R* range for English vowel-to-vowel coarticulation test words

2.1.1.4. Canonical Vowel Control Words

For the purpose of comparison with the coarticulated vowels in the CVCV words, a set of 72 words containing canonical versions of the vowels in the test words (i.e., containing vowels *not* coarticulated with another vowel) were included in the corpus. There were 8 words for each of the 9 vowels present in the CVCVs: /i/, /ɛ/, /æ/, /ɑ/, /ʌ/, /u/, /eɪ/, /aʊ/, /oʊ/. Canonical vowel control words were all monosyllabic words of the form CVC, CV, VC, or, in one case, V.

Because Wright (1997, 2004) found that vowels in high-*R* words are more centralized than those in low-*R* words, all canonical words had a low relative frequency to ensure that they would be as extreme (and therefore as "canonical") as possible. The canonical words, along with their log frequencies, neighborhood densities, and relative frequencies, are listed in Appendix 3.

2.1.1.5. Summary of Corpus

Exemplifying	Nasal Coartic.	CVN	40
		NVC	48
	V-to-V Coartic.	CVCV	
		CVC/i/	24
		CVC/o/	12
		V-matched	12
		(V-mat. & CVCo)	(3)
	Canon. Vowels	CVC	50
		CV	14
		VC	7
		V	1
		TOTAL	205

Table 3 Summary of the main corpus, showing the total number of words of each type; in all categories except Canon., each type contains an equal number of high-*R* and low-*R* words.

2.1.2. Subjects

Twelve pairs of subjects participated in the data collection experiment. In each pair, there was one talker and one listener. All subjects were native speakers of American English, and all talkers were native speakers of a California variety of American English. It was important to choose a linguistically homogeneous group of talkers to ensure that their mental lexicons would be as similar as possible and as similar as possible to the lexicon assumed in the designing of the corpus. In addition to having similarly sized vocabularies, it was assumed, for instance, that talkers would not have an /a/ - /ɔ/ distinction and would not neutralize /ɪ/ and /ɛ/ before nasals. Of the talkers, 8 were female and 4 were male. Among the listeners, there were 7 females and 5 males.

All were students or staff at universities in Southern California. None of the subjects were familiar with the purpose of the study, and all were paid $5 for their participation.

2.1.3. Procedure

Subjects participated in recording sessions lasting approximately 30 minutes. All sessions took place in a sound-attenuated booth. Subjects participated in pairs, one assigned to the role of talker and one assigned to the role of listener. If both subjects were Californian speakers, the roles were randomly assigned; otherwise, the Californian speaker was assigned to be the talker, and the other subject was the listener.

The subjects were seated facing one another, and the talker wore a head-mounted microphone. A computer screen was positioned so that the talker could see it but the listener could not. The subjects were instructed that the talker would dictate a list of simple English words to the listener, whose task it was to write down the words in order. Stimulus presentation was controlled by a script running on PsyScope software on a Macintosh computer (Cohen, et al., 1993). Words were presented one at a time in the center of the screen in a quasi-randomized order. (It was ensured that semantically-related words were separated by at least two test words.) The talker saw a word on the screen and said to the listener, "The first word is X." After uttering each word, he pressed a button to advance to the next word, which he would announce to the listener by saying, "The word after X is Y." To facilitate this task for the talker, the previous word (in the X position) was printed in a smaller font above the new target word. This procedure began with 12 practice tokens and continued until all 205 test words were uttered by the talker. A short break was provided one-third and two-thirds of the way through the word list to minimize boredom. Each new set started with a filler, non-test word.

The purpose of the paired-subject dictation task design was to promote an authentic listener-directed speech style despite the somewhat unnatural setting of the recording booth. Talkers were encouraged to remember to talk *to the listener*. They were told to glance at the computer screen to see each new word and then to direct their speech to their partner, who was trying to understand them and make an accurate list. They were also prohibited from repeating words or saying anything other than the scripted utterances; listeners were prohibited from asking for repetitions. Listeners were informed that their task was not a spelling test, and that in the case that a homophone was presented, either orthographic variant was acceptable.

This procedure generated two repetitions of each word for each speaker: one in sentence-final position, and the other in the "word after X" context. A comparison of the two repetitions was initially envisioned. However, the "word after X" context yielded a variety of focused and unfocused instances of test words with following prosodic phrase boundaries of different sizes and tonal patterns. Furthermore, it is the first mention that is most relevant for addressing the present questions, whether the effect being studied is communicatively-motivated or whether it is due to difficulty in lexical retrieval. Therefore, only the more consistently focused, utterance-final, first repetitions were analyzed.

Sessions were recorded digitally to DAT cassettes. The recordings were then downsampled to 22kHz and chopped into individual files containing each test word.

2.1.4. Measurements

2.1.4.1. Nasal Coarticulation

The degree of nasal coarticulation in the CVN and NVC words was determined by measuring the nasality of the nasal-adjacent vowel from the acoustic signal. Nasalized vowels show the presence of extra spectral peaks at low frequencies, generally one below the first formant (Hattori, Yamamota, and Fujimura, 1958; Lindqvist-Gauffin and Sundberg, 1976), and another peak around 1 kHz (House and Stevens, 1956; Maeda, 1982; Huffman, 1990). Furthermore, a reduction in the amplitude of the first formant spectral peak has been observed to accompany nasalization (House and Stevens, 1956). The acoustic manifestation of vowel nasalization may be quantified, then, by examining the relative amplitudes of these nasal peaks and the first formant. For non-high vowels (where F1 is relatively high), the acoustic correlate A1-P0, where A1 is the amplitude of the first formant (as represented by the amplitude of the peak harmonic closest to the expected F1) and P0 is the amplitude of the low frequency nasal peak (as represented by the amplitude of either the first or second harmonic, depending on the speaker), has been found to be the most reliable measure of vowel nasality (Chen, 1996, 1997).

A1 and P0 were measured from 1024 point FFT spectra generated with a 25 ms Hamming window using MultiSpeech analysis software (Kay Elemetrics). Measurements were made at three points in the vowel: the onset, the midpoint, and the end. For the onset, the left edge of the analysis window was aligned with the beginning of the vowel; for the midpoint, the window was centered on the midpoint; and for the end, the right edge of the analysis window was aligned with the end of the vowel. Measurements were made at three locations in order to observe any differences between vowel portions closer to or further away from the nasal consonant, and also to ensure that the most nasal portions of the vowel were measured for a given speaker since the time course of vowel nasalization can vary somewhat across speakers (Cohn, 1990).

2.1.4.2. Vowel-to-Vowel Coarticulation

The degree of vowel-to-vowel coarticulation in the CVCV words was determined by examining the Euclidean distance in the F1 by F2 space between each vowel and a mean canonical (i.e., non-coarticulated) vowel of the same quality for a given talker. The individual contributions of each formant were also evaluated by comparing the F1 and F2 of each vowel with the mean F1 and F2 values of the matched canonical vowel. (In addition to revealing any height vs. front-back asymmetries, the individual formant measures allowed for direct comparison of the current data with the data from Brown (2001) in which coarticulation was calculated only on this basis.) The coarticulatory influence of one vowel on the other would be realized as increased distance from canonical, in other words, as a raising or lowering of F1 or F2 or both, depending on the qualities of the vowels. Therefore, the Euclidean distance between the test vowel and a canonical vowel of the same quality was interpreted as the amount of coarticulation, and the absolute values of the differences between the F1 and F2 values of the test vowel and the canonical vowel were interpreted as the individual formant contributions to the amount of coarticulation.

However, deviation from canonical is not, in and of itself, evidence of coarticulation. To be confident that the deviation that was interpreted as vowel-to-vowel coarticulation was in fact due to influence from the cross-consonantal vowel, the Euclidean distance between the test vowel and a canonical instance of the *influencing* vowel was also calculated. A test vowel that is closer to the cross-consonantal vowel shows more coarticulation with that vowel. The various vowel-to-vowel coarticulation measures are illustrated in Figure 6.

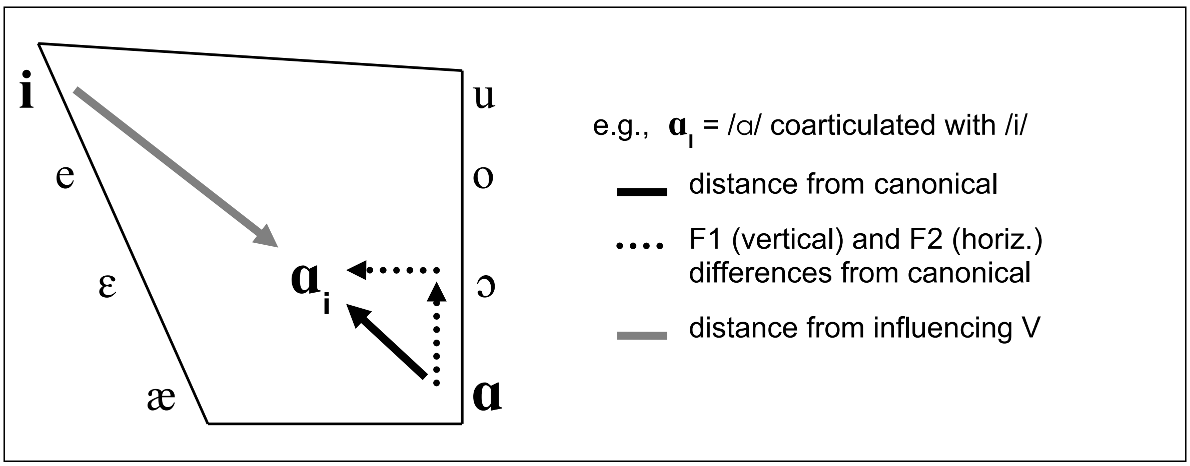

Figure 6 Vowel-to-vowel coarticulation measures. $ɑ_i$ represents an /ɑ/ coarticulated with an /i/. The solid black line represents the Distance from Canonical measure; the dotted lines represent F1 and F2 contributions to the distance from canonical; the solid gray line represents the distance from the influencing vowel.

Measurements were made at 5ms intervals in the 20ms region of the test vowel closest to the influencing vowel, where V-to-V coarticulation is known to occur most notably. Measurements were also taken at the test vowel midpoint. Measurement points are shown in Figure 7. Points will be referred to by their temporal distance from the vowel edge: 5ms, 10ms, 15ms, 20ms. Thus, for both V1 and V2, the 5ms point is 5ms from the intervening consonant, but for V1, this is the chronologically *last* point in the vowel, whereas it is the first point for V2.

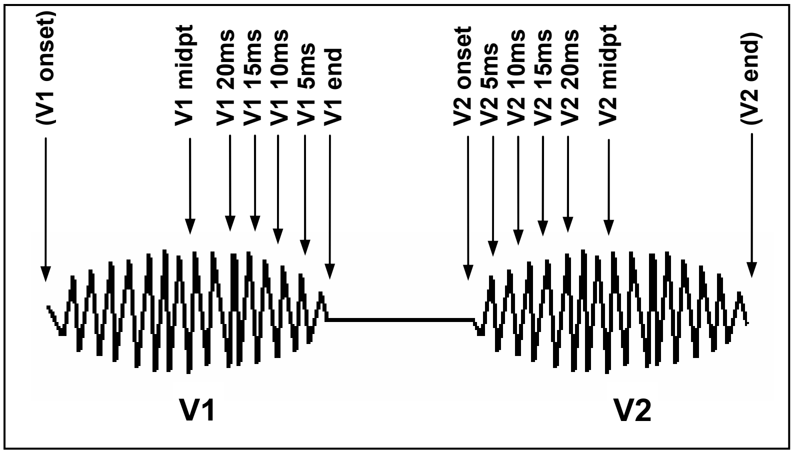

Figure 7 Schematic of a VCV sequence showing vowel formant measurement points

Measurements were taken from the numerical output of a formant track performed for a selected vowel using PCquirer acoustic analysis software (Scicon RD). Formant tracking was based on repeated LPC analyses performed automatically throughout the vowel. Formant values were verified by visual examination of wide band spectrograms to ensure that no spurious values were included. All frequencies in Hertz were converted to the auditorily-scaled Bark scale using the formula B=26.81/(1+(1960/f))–0.53, where B is bark and f is frequency in Hertz (Traunmüller, 1990). (This conversion formula provides highly accurate Bark estimates for frequencies in the ranges of F1 and F2.) Bark transformations were used because the current study is especially concerned with the auditory salience of any acoustic differences that are found. Additionally, the transformation allows for the direct comparison of F1 and F2 differences.

Canonical vowels were measured in the same manner. For these vowels, however, measurements were made just at the vowel midpoint in order to ensure as little contextual influence (from adjacent segments) as possible. The midpoint formant values for all canonical word vowels of a given quality were averaged. All references to canonical values in the calculation of distance or differences between coarticulated test vowels and canonical vowels, then, are based on the mean canonical vowel midpoint.

2.1.4.3. Vowel Reduction

The duration of each test vowel was measured to see whether duration was mediated by *R*. Durational reduction has been shown to vary with lexical frequency (Jurafsky, et al., 2000; Munson and Solomon, 2004), though it has been shown not to correlate with lexical measures depending more strongly on neighborhood density (Munson and Solomon, 2004). Also, durational measures allow us to look for a relation between durational reduction and coarticulation (Moon and Lindblom, 1994).

Vowel reduction/centralization was also calculated for all CVCV, CVN, and NVC vowels to compare with Wright's (1997; 2004) findings and to look at the interaction between reduction (as a vowel quality phenomenon) and coarticulation as accommodations to lexical confusability. Formant measures were taken at the midpoints of the vowels in the CVCVs as part of the coarticulation measurement procedure. The midpoints of the vowels in the CVNs and NVCs were additionally measured in the same manner. The distance from the center of the vowel space was then calculated, where the center of the vowel space was considered to be the center of gravity of the vowel space defined by the canonical vowel values for each talker. The canonical vowel formant values (the values averaged across the control vowel tokens for each vowel quality for a given talker, as used elsewhere in this study) were simply averaged to define the center (Bradlow, et al., 1996; Wright, 1997; Munson, 2004).

2.1.5. Statistical Analysis

The investigation of the effect of lexical factors on coarticulation undertaken in this dissertation relies on the comparison of the degree of coarticulation across words of different lexical confusability categories. These comparisons are evaluated based primarily on repeated measures analyses of variance (ANOVAs). In a repeated measures analysis, individual subjects are experimental units, and in this case, each data point is a value averaged over all of the words produced by a given talker in a given lexical confusability category. In the analyses in this dissertation, the main factor of interest is *R* (high-*R*, low-*R*). Position in Vowel (beginning, middle, end—for nasal coarticulation words, *or* 5ms, 10ms, 15ms, 20ms—for vowel-to-vowel coarticulation words) is also included, as is Set (CVC/i/, CVC/o/, V-matched) for vowel-to-vowel words. There are no between-subject factors. Because some of these factors have more than two levels, there is the potential for violation of the sphericity assumption, which states that the variances of difference scores for each pair of levels within an independent variable are equal. To correct for any violation of this statistical assumption, Huynh-Feldt corrected degrees of freedom were used in generating the *F* ratios and *p* values, and are reported as the degrees of freedom for the independent variable. In this study, results are considered to be significant if *p* values of less than 0.05 are obtained.

2.2. French Corpus

2.2.1. French Speech Materials

Tokens in the French corpus included 128 words exemplifying nasal coarticulation (both anticipatory and carryover).

2.2.1.1. Lexical Properties

French lexical statistics were determined from the Lexique lexical database (New, et al.), which is a corpus of 130,000 wordform entries taken from 31 million words of text and spoken dialog. This corpus was chosen to match as closely as possible the properties of the CELEX corpus used for English. As for English, raw frequencies were log transformed using a base-10 log transformation before relative frequency was calculated.

Relative frequency (*R)* for French differs from relative frequency for English in one significant way. While English frequencies and neighborhoods were calculated on the basis of lemma forms, French frequencies and neighborhoods were calculated on *word* forms. Lemmas seemed an inappropriate basis for these lexical calculations in French since in French, lemmas are less phonologically unified than in English. For instance, in French, the feminine and masculine forms of nouns and adjectives are often phonologically dissimilar enough to have completely different neighborhoods: compare *bon* [bõ] ‘good’ (masc.) and *bonne* [bɔn] ‘good’ (fem.), which share no segment but the initial [b]. Also, French verbs have more phonologically distinct inflections than English verbs, leading to the possibility of frequent verbal forms that do not match the “look-up form" of their lemma. Furthermore, the nature of the experimental task actually suggests that it is word form confusability that is most relevant. As in the English part of the study, talkers are told to dictate a list of *words* to a listener, whose task it will be to write them down correctly. So in this particular restricted communicative situation, it is critical that distinctions among individual words within a lemma be communicated, and meaning, in fact, plays no role[2].

Words were again selected for inclusion in the study on the basis of having *R* values at the upper or lower end of the range of *R* values for words of the same type. Absolute log frequency means and distributions were balanced across the two relative frequency conditions for each type of coarticulation. When a word was homophonous with other forms within the lemma, only the most frequent form was selected as a test word. Also, for low-*R* nouns with homophonous singular and plural forms, *R* was calculated both with the regular wordform frequency of the target word in the numerator and with the sum of the singular and plural wordform frequencies in that position (though it is the true wordform *R* that is reported here). Only words for which both *R* calculations

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[2] The fact that the task is communicative in nature is no different for the French part of the study than for the English part in which lemma frequencies were used in the calculation of *R*. The methodological support for the use of wordform frequencies in French would seem, then, to suggest that wordform frequencies should have been used for English as well. However, the use of lemma frequencies for English more closely matched the calculations used in other studies involving English neighborhoods. And in fact, even when *R* was recalculated for the English word list based on wordform frequencies, these words fell into the same basic high- and low-*R* categories.

yielded the same *R* category classification were chosen as test words. This was done to minimize the possibility that the wordform vs. lemma *R* calculation could lead to different kinds of sets of words in French as opposed to in English. Although no database of familiarity ratings was available for French, all words were verified as "familiar" by 3 native speakers of French. One of these speakers, a fluent French-English bilingual, further verified that the French words were of comparable familiarity to the words in the English study corpus.

2.2.1.2. Nasal Coarticulation Test Words

Nasal coarticulation test words were of essentially two types: disyllabic words with a nasal consonant in the final syllable coda (words of the form σ(C)VN) and disyllabic words with a nasal in the second syllable onset (words of the form σNV(C_0)). There was also a small number of monosyllabic CVN-type words in the anticipatory nasal coarticulation set. All the nasal coda words will be referred to as VN words and the nasal onset words, as NV words. The coarticulatory context of interest was chosen to be in the final syllable because it was expected that this was the syllable that would be produced with stress, making the set of words as similar as possible to the monosyllabic nasal words in the English corpus. In fact, however, some subjects produced initial stress when saying these words essentially as citation forms.

Disyllabic words were used for the French corpus rather than monosyllabic words (as in the English corpus) because almost all of the possible monosyllabic French forms have very low *R* values. Of the 610 possible monosyllabic (C_0)VN type words in the Lexique corpus, 95% have an *R* value less than .07, the low-*R* threshold ultimately adopted for the French disyllabic nasal words (and comparable to the one used for both the English CVCVs and the English nasal words). Only 11 monosyllabic French CVN words were possible high-*R* words by the thresholds used elsewhere. The situation for NV(C_0) type words is quite similar, again with 95% of the possible words having an *R* value less than .07. The *R* distributions for the groups of French *di*syllabic nasal words were much more like the *R* distributions for the English sets. However, the use of disyllabic nasal words left the choice of low-*R* nasal-contrastive VN words slightly limited; therefore, it was necessary to include a small number of monosyllabic CVN-type words in the nasal-contrastive anticipatory coarticulation set in order to fill out a vowel-balanced set of low-*R* words. The number of monosyllables was balanced to the extent possible across low-*R* and high-*R* groups. But as was discussed previously, the set of high-*R* monosyllabic words is quite limited. So the nasal-contrastive VN set includes 6 low-*R* and 2 high-*R* monosyllabic words.

There were a total of 64 VN words and 64 NV words. Half of the words in each group were low-*R* and half were high-*R*. Additionally, each group of nasal words (VN and NV) was further divided according to the phonological properties of the vowel. Recall that although vowel nasality is phonemically contrastive in French, not all vowels rely on this contrast. There are four phonemically nasal vowels, /ɛ̃, œ̃, ɑ̃, ɔ̃/ (though the status of /œ̃/ is marginal, as it has merged with /ɛ̃/ for many speakers), and 12 oral vowels, including the oral counterparts of the nasal vowels, as illustrated in Figure 8. Each group of French nasal words included two subsets, then: one containing words with *nasal-*

contrastive vowels (oral vowels *with* nasal counterparts), and one with *non-contrastive* vowels (oral vowels with *no* nasal counterpart).

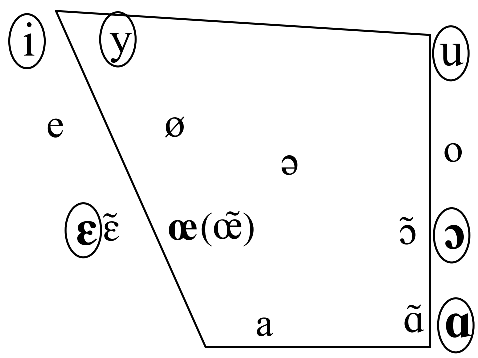

Figure 8 French vowel chart. Oral vowels with nasal counterparts are shown in bold type. Test vowels, both nasal-contrastive (in large bold) and non-contrastive (in large plain type), are circled.

Within each subgroup, vowel quality was balanced across hard and easy groups and, to the extent possible, across anticipatory and carryover groups. The identity of the nasal consonant (/n/, /m/, or /ɲ/) was nearly balanced across lexical confusability groups. Figure 9 schematizes the range of French nasal word types.

$$(\sigma)\ (\mathrm{C}) \left\{ /\mathrm{i}/,\ /\mathrm{y}/,\ /\mathrm{u}/ \right\} \mathrm{N}$$

$$(\sigma)\ (\mathrm{C}) \left\{ /\varepsilon/,\ /\alpha/,\ /\text{ɔ}/ \right\} \mathrm{N}$$

$$\sigma\ \mathrm{N} \left\{ /\mathrm{i}/,\ /\mathrm{y}/,\ /\mathrm{u}/ \right\} (\mathrm{C})$$

$$\sigma\ \mathrm{N} \left\{ /\varepsilon/,\ /\alpha/,\ /\text{ɔ}/ \right\} (\mathrm{C})$$

Figure 9 Nasal word types included in the French study corpus. There are 32 VN tokens (16 with contrastive vowels and 16 with non-contrastive vowels), and 32 NV tokens (16 with contrastive vowels and 16 with non-contrastive vowels).

As for the English corpus, absolute log frequency was balanced across lexical confusability groups for each type of coarticulation. Log frequency and *R* were also balanced across the vowel contrast groups (nasal contrastive and non-contrastive vowels). The mean log frequency and the mean and range of *R* values for words in each nasal coarticulation category are listed in Table 4. All VN and NV test words are listed in Appendix 4 with their log frequencies, neighborhood densities, and relative frequencies.

	VN - nasal contrastive V			NV - nasal contrastive V		
	log freq.	*R*	*R* range	log freq.	*R*	*R* range
Low-*R*	2.01	.044	.008 - .071	2.08	.041	.012 - .072
High-*R*	2.05	.369	.180 - .844	2.10	.450	.161 - 1.000
	VN - non-contrastive V			NV - non-contrastive V		
	log freq.	*R*	*R* range	log freq.	*R*	*R* range
Low-*R*	2.00	.062	.017 - .084	2.13	.044	.010 - .069
High-*R*	2.03	.474	.155 - 1.000	2.12	.390	.166 - 1.000

Table 4 Mean Log Frequency, Mean Log Relative Frequency (*R*), and *R* range for nasal coarticulation test words

2.2.1.3. Summary of Corpus

Exemplifying Nasal Coartic.	VN	
	nasal-contrastive V	32
	non-contrastive V	32
	NV	
	nasal-contrastive V	32
	non-contrastive V	32
	TOTAL	128

Table 5 Summary of the French corpus, showing the total number of words of each type. Each type contains an equal number of high-*R* and low-*R* words.

2.2.2. Subjects

Eight subjects participated in the data collection experiment. All were native speakers of French from France; 3 were female and 5 were male. Although the length of their time in the United States varied widely (from 2 weeks to more than 10 years), all had at least completed high school in France before leaving. The degree of their English bilingualism, however, could not be experimentally controlled for. Subjects were all university students or staff, and none were familiar with the purpose of the study. Subjects were offered $5 for their participation.

2.2.3. Procedure

The French recording procedure was as similar to the English procedure as possible, with the significant difference that subjects participated individually rather than in pairs to maximize the number of available talkers, since French speakers were more difficult to recruit than English speakers.

To encourage the same style of listener-directed speech that was elicited in the English part of the study, but in the absence of a listener, talkers were told that their recordings would be heard by native French listeners in a later study. As in the English procedure, they were instructed that they would be dictating a list of simple French words that a listener would later have to listen to and write down in order. To make the task more authentic, talkers were asked to pause between items to allow the hypothetical future listener time to write down each word. As in the English procedure, subjects were told that the listener would not have to distinguish homophones.

Stimuli were presented by computer, as in the English procedure. There were 10 practice tokens, followed by 224 monosyllabic and disyllabic test words, 128 of which are analyzed in this study. Words were recorded in the following carrier sentences: "Le premier mot est X" ('The first word is X'), and then, "Le mot après X est Y" ('The word after X is Y'). Two short breaks were provided, and each new set of words started with one or two filler, non-test words.

2.2.4. Measurements and Analysis

2.2.4.1. Nasal coarticulation

Recall that vowel nasalization may be quantified by examining the relative amplitudes of one of two nasal peaks and the first formant. One of the nasal peaks, P0 (as discussed in section 2.1.4.1 above), is found at a very low frequency, near the first or second harmonic. The other nasal peak, P1, is found near 1000 Hz. In non-high vowels, where F1 is consistently above P0, A1-P0 is calculated as a measurement of nasality. For high vowels, however, where F1 is relatively low and might be confused with or interfere with P0, the acoustic correlate A1-P1 using the amplitude of the higher frequency nasal peak (as represented by the amplitude of the peak harmonic near 1000 Hz), is more reliable as a measure of vowel nasality (Chen, 1996, 1997). Therefore, in the French data, where both high and non-high vowels are included in the corpus, A1-P1 was calculated for the high vowels (i.e., the non-contrastive vowels) and A1-P0 was calculated for the non-high vowels (i.e., the nasal-contrastive vowels). (Only vowels measured in the same way were directly compared with one another.) Measurements were made following the procedure described in section 2.1.4.1 for the English corpus.

2.2.4.2. Vowel Reduction

As in the English corpus, vowel duration was measured for all test vowels. Measurements of reduction/centralization were not made for the French data.

2.2.4.3. Statistical Analysis

Statistical analyses were performed as in the English part of the study.

Chapter 3: Effects of Lexical Confusability on Coarticulation in English

The fundamental questions of interest in this dissertation concern whether and how coarticulation is constrained by lexical factors. To address this question at its most basic, the degree of coarticulation in high-*R* and low-*R* words was compared, testing the following hypothesis:

> **Hypothesis 1 a:** There is an effect of lexical confusability (i.e., *R*) on the degree of coarticulation produced in a word.

Furthermore, it is expected, based on the findings in Brown (2001), that the effect will occur in a particular direction, as stated in the following more specific hypothesis:

> **Hypothesis 1 b:** Low-*R* ("hard") words exhibit a greater degree of coarticulation than high-*R* ("easy") words.

These hypotheses are intentionally very general, broadly predicting an effect on coarticulation, without any stipulations about the type of coarticulation. However, the previous body of data on lexical effects on coarticulation provided only a very limited basis for making such a prediction. To extend the current data on the phenomenon and assess whether any effects found for particular cases of coarticulation may be assumed to apply to coarticulatory processes in general (in other words, to see if the effects are robust across types of coarticulation), four different cases of coarticulation are examined here: anticipatory and carryover nasal coarticulation and anticipatory and carryover vowel-to-vowel coarticulation. These cases were chosen because they represent, in a small number of cases, a broad range of potential coarticulatory situations: various segmental influences—both consonantal and vocalic, single and multiple articulator involvement, and anticipatory and carryover effects.

These factors in coarticulation might interact with the lexical effect of interest due to either their articulatory or perceptual consequences. From the talker's perspective, factors relating to what is actually easy to say or, on the other hand, particularly effortful might play a role. If the motivation for coarticulation is to facilitate the act of articulating, types of coarticulation that have a greater effect on overall articulatory effort might be more likely to be involved (perhaps especially so in hard words, if they are hard for listeners as well). If the coarticulation is a direct consequence of difficulty in lexical access and changes in timing, types of coarticulation involving bigger movement or slower articulators might show a greater response to lexical factors. Applied to the cases being considered in the current study, lowering the velum as in nasal coarticulation may be a minimally effortful gesture, particularly relative to moving a larger articulator like the tongue, as in adjacent vowel articulations, for which reducing effort might have greater benefits to a talker. Even if the effect of lexical factors on coarticulation is the result of a genuinely listener-directed adjustment, these articulatory factors could still play a constraining role. Talkers might, for instance, be less likely to make these accommodations when they are more effortful.

In fact, one can imagine a number of coarticulatory factors that might have perceptual consequences for a lexical effect on coarticulation. Certain coarticulatory cues have more salient perceptual consequences than others. Furthermore, some provide more useful acoustic information, perhaps leading these types of coarticulation to be increased more in hard words than other types. On the other hand, it might be that certain types of coarticulation actually mask important acoustic cues (in ways that listeners are unable to unravel, at least efficiently), actually hurting more than helping. If the basis for lexical effects on coarticulation is the accommodation of listener difficulties, then these types of coarticulation would not be predicted to increase (and might, in fact, decrease) in “hard” words. (It may be noted, however, that even in studies of assimilation, which might be analogous to cases of extreme coarticulation in which one segment masks another, it has been shown that listeners are remarkably good at recovering the ostensibly assimilated segment. In C_1C_2 clusters, where C_1 is assimilated to C_2, listeners continue to perceive C_1 until the gestures for the two consonants are at least 100% overlapped (Byrd, 1992; also Hardcastle, 1994).)

With similar considerations in mind, different cases of coarticulation can also be classified according to the articulators that are involved. Some types of coarticulation involve two (or more) segments that make use of different articulators, leading to gestural overlap, while other types involve a single articulator for both segments, leading to gestural accommodation or compromise. One might imagine that the cues provided by overlap were more accessible to listeners than those from gestural compromise since in the overlap case, both gestures are fully present, whereas in the compromise case, both are modified. If, in fact, these perceptual consequences are correct, and if the lexical effects are perfectly listener-oriented, Hypothesis 1 might have to be modified to specify effects for only multiple articulator types of coarticulation:

Hypothesis 2 (Auxiliary[3]) : Coarticulation involving multiple articulators will show an effect of *R* (such that it will be increased in "hard" words) while single-articulator types will not.

With direct reference to the cases being investigated in the current study, nasal coarticulation is a case in which the two relevant articulators, the tongue for the vowel and the velum for the nasal, are able to act independently of one another. Both anticipatory and carryover nasal coarticulation are attested in English, and in fact, nasal coarticulation is quite extensive. Coarticulation in the anticipatory direction is often thought to exceed nasal coarticulation in the carryover direction, though Cohn (1990) finds roughly the same pattern and degree of nasalization in both directions (with a tendency towards slightly more in the carryover case). (See Cohn (1990) for a fuller description of the patterns of nasal coarticulation in English.)

With vowel-to-vowel coarticulation, a single main articulator, the tongue, is involved in the articulation of both vowels. Carryover vowel-to-vowel coarticulation generally exceeds anticipatory V-to-V coarticulation in English, though both types are consistently exhibited in both F1 and F2 (with F2 usually showing a stronger effect) (Fowler, 1981). V-to-V effects are strongest near vowel transitions, but lingual vowel-to-

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[3] Throughout the dissertation, certain possible, sometimes conflicting, hypotheses will be presented that are not actually part of the predictions of the current study. They will be referred to as auxiliary hypotheses. Their purpose is often to suggest motivations for various parts of the experimental design, but they are not in all cases explicitly tested as part of the design.

vowel coarticulatory effects have sometimes been found extending into the steady-state period of the vowel (Fowler, 1981; Magen, 1985), and even across an entire syllable from V1 to V3 (Magen 1997).

It is further of interest to examine coarticulation in both directions. Anticipatory and carryover coarticulation have different treatments in certain traditional theories of coarticulation with respect to their respective origins and control. Anticipatory coarticulation has been traditionally considered to be phonological, under the control of the speaker. Carryover coarticulation, on the other hand, has been analyzed as phonetic and therefore automatic and out of the control of the speaker (e.g., Lindblom, 1963; MacNeilage, 1970).

Anticipatory and carryover coarticulation might also be predicted to differ in their receptiveness to an effect of *R* based on the potential usefulness of the cues which they can provide (predictive or reinforcing). Models of word recognition differ with respect to their position on the course of recognition over time. It is sometimes assumed that lexical processing proceeds from left to right, and that the process of recognizing a word occurs continuously as the word is heard (e.g., Marslen-Wilson and Welsh, 1978; Warren and Marslen-Wilson, 1987). If this is correct, and especially if adjustments in degree of coarticulation that are mediated by lexical factors are aimed (consciously or not) at facilitating lexical perception, we might suppose that anticipatory and carryover coarticulation would be differently affected by lexical factors. Anticipatory coarticulation might show a greater lexical effect, as this type of coarticulation would result in earlier and potentially predictive cues to a segment. If this were absolutely true, however, and coarticulation were perfectly listener-directed, we would predict that languages would universally exhibit more anticipatory than carryover coarticulation, but this is not the case. (See Sharf and Ohde (1981) for a review of cross linguistic patterns of the direction of coarticulation.) Therefore, although Hypothesis 1 (in both of its parts) predicts that an effect of *R* will be found for both anticipatory and carryover coarticulation, both directions of each type of coarticulation will be compared in order to examine the relative importance of the effect in the two cases, with the following hypothesis:

> **Hypothesis 3 :** The difference in degree of coarticulation between high-*R* and low-*R* words is greater for anticipatory than for carryover coarticulation.

With respect to the case of vowel-to-vowel coarticulation, there is a further reason to suppose that there might be a difference in effect between the two directions, which is unrelated to the directionality itself. Because all V-to-V coarticulation words are disyllabic, of the form CV́CV with initial stress, there is always a difference in stress conditions between anticipatory and carryover coarticulation. Lexical effects on production have not been much examined in polysyllabic forms, and comparisons across syllables have not been made. Therefore, it is unknown whether both syllables, stressed and unstressed, are affected by factors of the lexicon. There is no reason a priori to believe that lexically-based adjustments in production will be affected by stress. However, it has been claimed that stressed syllables exhibit coarticulatory effects on unstressed syllables, but are themselves relatively resistant to coarticulation (Fowler, 1981; de Jong, et al., 1993). Such an interaction between stress and lexical effects might lead to the following hypothesis:

> **Hypothesis 4 (Auxiliary):** The effects of *R* on coarticulation are seen from stressed onto unstressed syllables, but not the reverse. (Among the CVCV test words, which all have initial stress, a difference in degree of carryover coarticulation between easy and hard words is expected then, while an effect in the anticipatory direction is not.)

However, because in English, most unstressed vowels are categorically reduced to schwa, it is unclear whether the stress effect on coarticulation found by Fowler and de Jong is even due to stress itself, or to the extreme reduction present in unstressed syllables. If *unreduced* unstressed vowels (like all of the vowels in the test words) are not limited in their ability to coarticulate, we might actually make an opposite prediction. If the coarticulation effect is perceptually meaningful (in other words, if its purpose is to provide additional information to a listener), it might be the case that it would actually be realized on privileged stressed syllables rather than on unstressed syllables, as stated in the following auxiliary hypothesis:

> **Hypothesis 5 (Auxiliary):** The effects of *R* on coarticulation are seen on stressed syllables but not on stressless ones. (Among the CVCV test words, then, a difference in degree of anticipatory coarticulation between easy and hard words is expected while an effect in the carryover direction is not.)

Finally, in this chapter, the effect of lexical confusability on reduction (both durational reduction and centralization) will be addressed. It is hypothesized that previous results by Munson and Solomon (2004) regarding durational reduction and by Wright (1997, 2004; see also Munson and Solomon (2004)) regarding centralization will be replicated in the current data:

Hypothesis 6 : *R* has no effect on durational reduction: there is no systematic difference in duration between vowels in low-*R* words and those in high-*R* words.

Hypothesis 7 : Low-*R* words show less vowel space reduction (centralization) than high-*R* words. (Differently stated, vowels in low-*R* words are more peripheral in the vowel space than those in high-*R* words.)

The reduction results are of interest not only to replicate previous findings and to confirm that the current data and their lexical confusability classifications are consistent with those used in previous studies, but also because both types of reduction have the potential to affect coarticulation. A systematic difference in duration between high-*R* and low-*R* words could yield a systematic difference in the peripherality of vowels (Moon and Lindblom, 1994). And, as was discussed in Chapter 1, a difference in peripherality of vowels could yield a difference in degree of coarticulation. Thus, the relation between these phenomena merits further investigation and discussion so that the nature of the coarticulation effect of interest in this dissertation can be better understood.

3.1. Nasal Coarticulation Results

Recall that for nasal coarticulation, a spectral measurement of nasality (A1-P0) was made at three timepoints throughout each test vowel: onset, midpoint, and end. Lower A1-P0 values are indicative of *greater* nasality.

3.1.1. Anticipatory (CVN)

For a majority of subjects in most positions overall, low-*R* CVN words show smaller mean A1-P0 values than high-*R* CVNs. At the end position, the data for 11 of 12 subjects show lower mean A1-P0 values for low-*R* words than for high-*R* CVNs, suggesting that the vowels in the low-*R* words are more nasal relative to high-*R* words at the point nearest the influencing nasal consonant. Low-*R* words also show smaller A1-P0 values than high-*R* words for 9 of the 12 subjects at the onset and for 8 of the subjects at the midpoint. However, it is not the case that certain subjects simply show a different pattern across the board; each of the subjects shows the low-*R* less than high-*R* pattern of means in at least one of the positions, and 11 of them show the pattern in at least two positions. It can also be observed that A1-P0 values for individual subjects and those averaged across subjects become progressively smaller from the beginning to the end of the vowel, indicating that the vowels were more nasal closer to the nasal consonant.

A two-way repeated measures ANOVA with nested within-subject factors of *R* (High vs. Low) and *Position* (Beginning vs. Midpoint vs. End) was performed on the A1-P0 values (pooled across items for each subject). The analysis showed a significant main effect of *R* [$F(1,11) = 6.39$, $p = .03$], as well as an effect of Position [$F(1.27,11) = 26.18$, $p < .0001$], but there was no *R* by Position interaction. These results reflect that the low-

R, or "hard," words, had more nasalized vowels (i.e., lower A1-P0 values) than the high-*R*, or "easy," words throughout the vowel. Furthermore, vowels were more nasal at points closer to the nasal consonant. The effects at all positions for the CVN words are summarized in the graph in Figure 10. (Note that there is no special significance to the zero-crossing. Negative A1-P0 values are simply smaller (i.e., indicating more nasality) than positive values.)

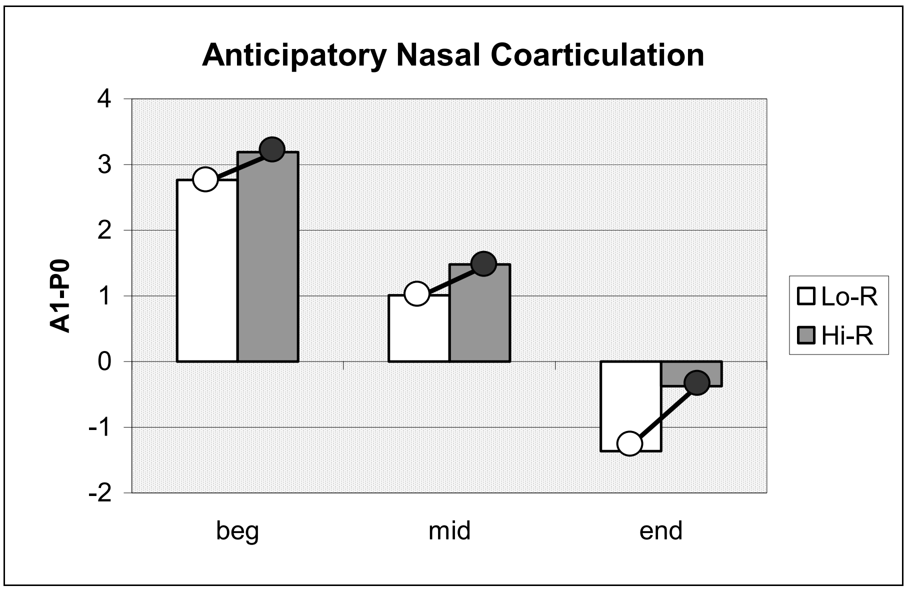

Figure 10 A1-P0 (representing anticipatory nasal coarticulation) in low-*R* vs. high-*R* CVN words. Low-*R* words are more nasal throughout the vowel than high-*R* words. (A1-P0 decreases as nasality increases.)

3.1.2. Carryover (NVC)

Among NVC words, low-*R* words again showed smaller mean A1-P0 values than high-*R* words for a majority of subjects and positions. At the beginning of the vowel, closest to the influencing nasal consonant, 10 of the 12 subjects show smaller A1-P0 values for low-*R* than for high-*R* words. This pattern of data also obtains for 9 of the 12 subjects at the midpoint and for 11 of the subjects at the end. All of the subjects show this pattern of means in at least two measurement positions.

A two-way repeated measures ANOVA with nested within-subject factors of *R* (High vs. Low) and *Position* (Beginning vs. Midpoint vs. End) was again performed on the A1-P0 values. The analysis showed a main effect of *R* [F(1,11) = 11.10, p = .002], but there was no effect of Position in this case and no interaction of *R* and Position. These results reflect that low-*R*, or "hard," words, have more nasalized vowels (i.e., lower A1-P0 values) than high-*R*, or "easy," ones with no evidence of any reliable differences throughout the vowel. The effect of *R* for all positions is summarized in the graph in Figure 11.

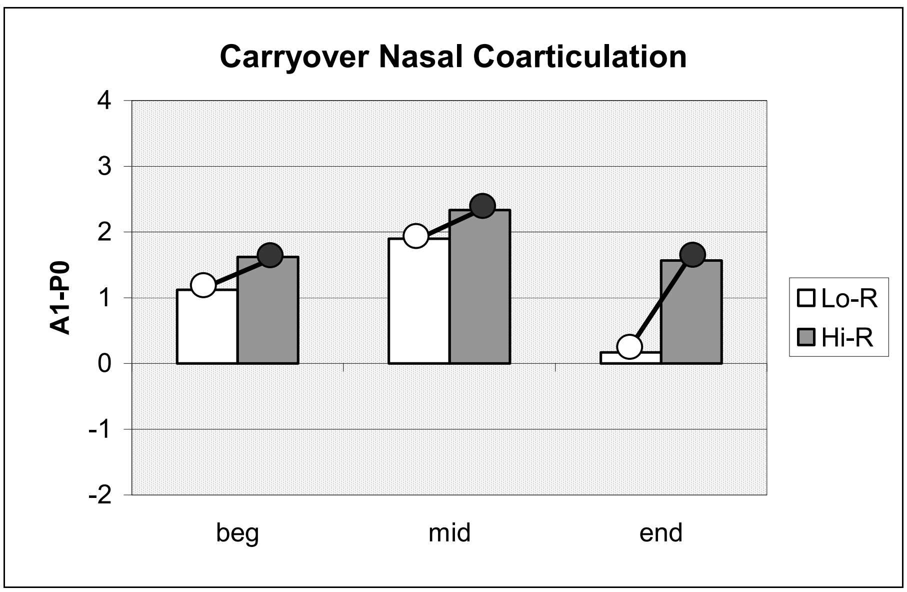

Figure 11 A1-P0 (representing carryover nasal coarticulation) in low-*R* vs. high-*R* NVC words. Low-*R* words are more nasal throughout the vowel than high-*R* words. (A1-P0 decreases as nasality increases.)

3.1.3. Comparing Directions of Nasal Coarticulation

Ignoring the lexical factor for a moment and comparing the anticipatory and carryover directions of nasal coarticulation, we can see that anticipatory nasal coarticulation is greater in magnitude at its most extreme (i.e., adjacent to the nasal consonant) than carryover coarticulation (A1-P0 is lower, indicating greater nasality), but the carryover coarticulation is maintained further throughout the vowel, as shown in Figure 12. The magnitude of the difference in A1-P0 between easy and hard, however, is quite similar both across positions and across directions of coarticulation. Because there was no interaction of Position and *R* found for either anticipatory or carryover coarticulation, across-position means can be used to represent the overall degree of nasality in each condition, simplifying the comparison. Figure 13 shows an *R* effect difference of .63 dB for anticipatory and a .75 dB difference for carryover coarticulation. A within-speaker paired t-test indicated that the magnitude of the difference in nasality across *R* conditions was no different in anticipatory than in carryover coarticulation [$t(11) = .44$, $p = .66$].

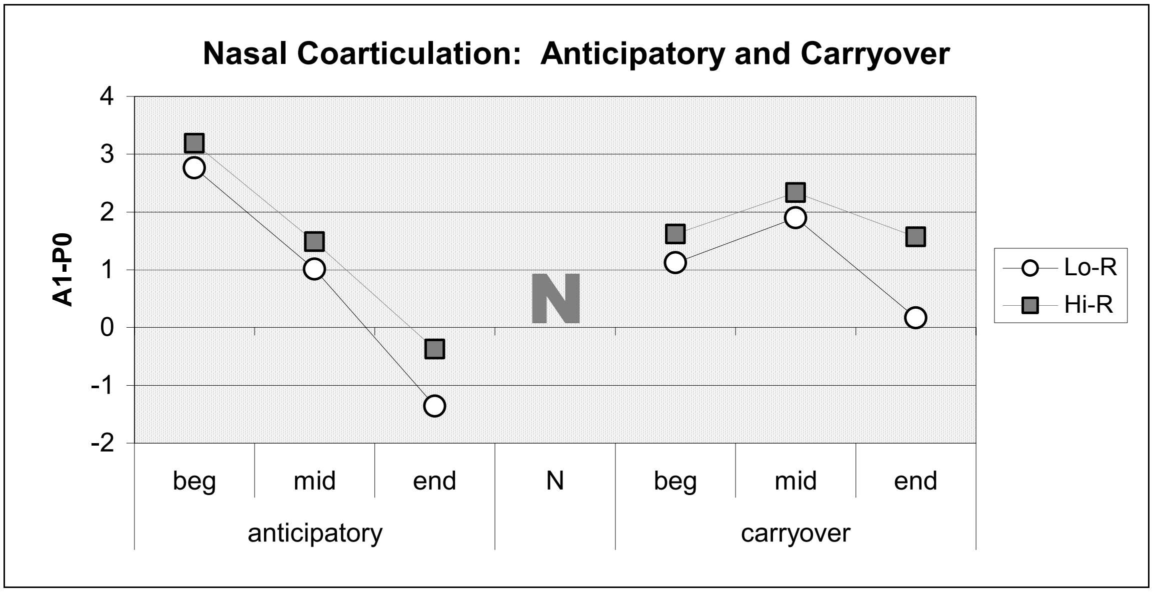

Figure 12 Anticipatory and carryover nasal coarticulation (A1-P0) across measurement positions.

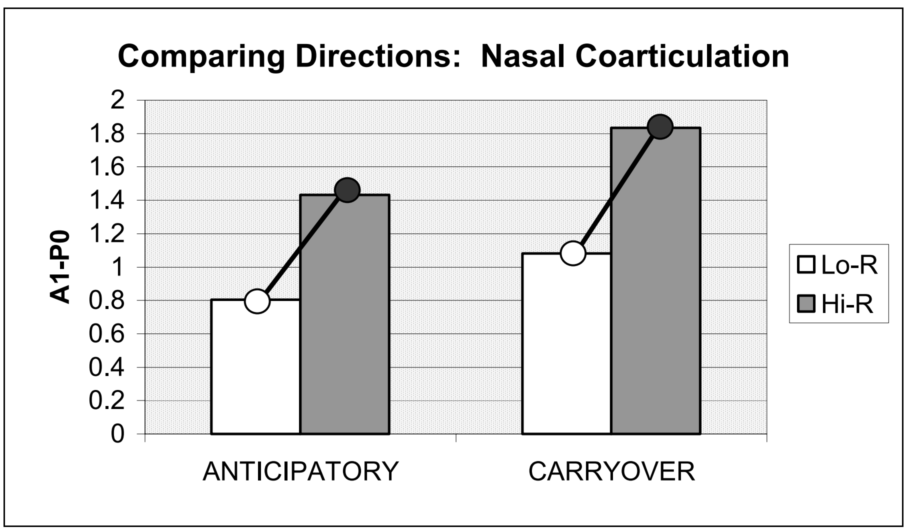

Figure 13 Comparing directions of nasal coarticulation: mean A1-P0 for low-*R* vs. high-*R* words.

3.2. Vowel-to-Vowel Coarticulation Results

For vowel-to-vowel coarticulation, recall that the amount of coarticulation was measured as the F1 by F2 Euclidean distance from a canonical vowel, calculated at 5ms intervals throughout the inside edge portion of each test vowel (the portion adjacent to the intervocalic consonant). (The point at the vowel edge, immediately adjacent to the intervocalic consonant, was ignored to avoid measuring strong consonantal effects.) To verify that the deviation was in an appropriate coarticulatory direction, the Euclidean distance from the cross-consonantal vowel canonical values was also calculated for each measurement point. And the individual contributions of the first two formants to the overall degree of coarticulation were measured as deviations from the F1 and F2 values of a canonical vowel.

3.2.1. *Anticipatory (V2 to V1)*

Since anticipatory vowel-to-vowel coarticulation involves the influence of V2 on V1 in CVCV words, V1s were compared with their canonical counterparts.

3.2.1.1. Distance from canonical

The distances from canonical for each test vowel (V1), pooled across items within each lexical confusability category, were submitted to a three-way repeated measures ANOVA with nested within-subject factors of *R* (High vs. Low), Position (5ms, 10ms, 15ms, 20ms), and Set (CVCi, CVCo, V-matched). The analysis showed a significant main effect of *R* [$F(1,11) = 20.00$, $p = .001$], confirming that the first vowels in low-*R* ("hard") words are further in acoustic space from their canonical vowel counterparts than those in high-*R* ("easy") words. Both of the other main effects were found to be significant as well. Post-hoc Fisher's PLSD pairwise comparisons indicated that the significant effect of Position [$F(1.47, 11) = 3.93$, $p = .05$] was due to significant differences between the 5ms point and the 15ms and 20ms points, showing that vowels were further from canonical at points in the vowel closer to the influencing other vowel. The significant effect of Set [F(1.91, 11) = 42.8, p < .0001] was reflected in significant pairwise differences among all three sets: CVC/o/s showed the greatest distance from canonical, followed by the V-matched set and then the CVC/i/s. Critically, there was no interaction of *R* by Position, indicating no difference in the *R* effect across positions. The effect in anticipatory coarticulation test vowels is summarized in Figure 14a-d. Sets are graphed separately to simplify the presentation.

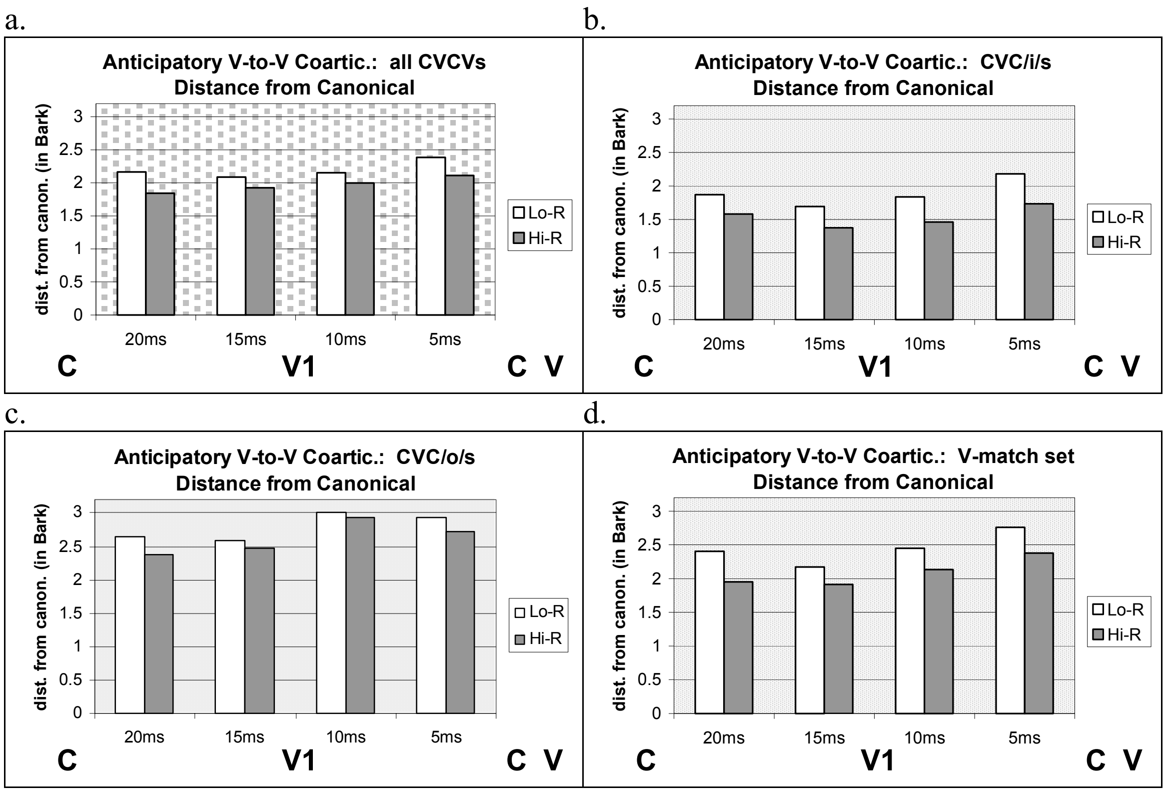

Figure 14 Anticipatory Vowel-to-Vowel Coarticulation: Distance from Canonical (in Bark) for all CVCVs. Note that timepoints are shown in their temporal order from 20ms to 5ms. There is a significant effect of *R* overall; any differences across set with respect to the *R* effect are not significant in this analysis.

3.2.1.2. F1 and F2 individual contributions

Mean F1 and F2 differences in V1 for each lexical category were also submitted to three-way repeated measures ANOVAs with within-subject factors of *R*, Position, and Set. The analysis for the first formant showed a significant effect of *R* [$F(1,11) = 8.68$, $p = .01$], indicating that, for V1, low-*R* CVCV words differ more from canonical with respect to F1 than high-*R* CVCVs. There was also a significant effect of Set [$F(1.74,11) = 38.6$, $p < .0001$] due to the fact that there was more F1 deviation in both CVC/i/s and CVC/o/s than in V-matched words, as revealed by Fisher's PLSD post-hoc comparisons. Finally, a significant interaction of Position by *R* was found, reflecting the fact that there was a greater difference between high-*R* and low-*R* words at the 5ms point than at the other points.

Analysis of the second formant similarly revealed main effects of both *R* [$F(1,11) = 10.14$, $p = .009$], indicating greater F2 deviation from canonical for low-*R* words, and Set [$F(2,11) = 62.42$, $p < .0001$], due to greater F2 deviation for CVC/o/s and V-matched words than for CVC/i/s. There were no other significant effects or interactions.

These results indicate that both F1 and F2 contribute to the effect of *R* on the degree of anticipatory vowel-to-vowel coarticulation. In terms of articulation, this means that there was increased anticipatory vowel-to-vowel coarticulation on both the frontness-backness dimension and on the height dimension in CVCV words.

3.2.1.3. Distance from opposite V as indication of V-to-V coarticulation

It has been assumed thus far that the deviations from canonical that were found in the vowels in the CVCV test words were evidence of vowel-to-vowel coarticulation.

However, to verify that the deviation could in fact plausibly be due to coarticulation, it must also be demonstrated that the deviation is in the direction of the influencing vowel. The Euclidean distance between vowels and their opposites (the V2s across the intervocalic consonant) was also calculated and pooled across items within each lexical confusability category. The mean distances for each talker were submitted to a three-way repeated measures ANOVA with within-subject factors of *R*, Position, and Set. The analysis confirmed that the first vowels in low-*R* ("hard") words were closer in acoustic space to their opposite vowels than those in high-*R* ("easy") words, showing a significant main effect of *R* [$F(1,11) = 10.64$, $p = .008$]. There were also main effects of Position [$F(2.03,11) = 5.49$, $p = .01$] and Set [$F(1.55,11) = 55.34$, $p < .0001$]. Fisher's PLSD post-hoc pairwise comparisons indicated that V1s in both CVC/o/s and V-matched words are closer to the cross-consonant V2 than CVC/i/s, and, unsurprisingly, that test vowels were acoustically closest (i.e., most similar) to the cross-consonantal vowel at the 5ms point where they are also temporally closest. There were no significant interactions, indicating that the effect of *R* was consistent across positions and sets.

In Figure 15, a vowel plot shows the distance between low-*R* and high-*R* vowels and the influencing vowel /i/ for CVC/i/ words. Although CVC/o/s and V-matched words show similar patterns of means, it is not appropriate to examine plots of distances for individual vowels for the CVC/o/s and V-matched words. Although both V1 and the following consonant were balanced across lexical confusability groups, individual high-*R* and low-*R* words could not be perfectly matched for both V and the intervening C simultaneously. Therefore, due to the small number of words with a given V1 (sometimes a single word), a comparison of the vowels in hard and easy words would be too much affected by idiosyncratic segmental context to be meaningful or generalizable. In the CVC/i/ set, however, where there were more potential experimental items, individual low-*R* words were matched to individual high-*R* words based on V1, place of articulation of C, and absolute frequency.

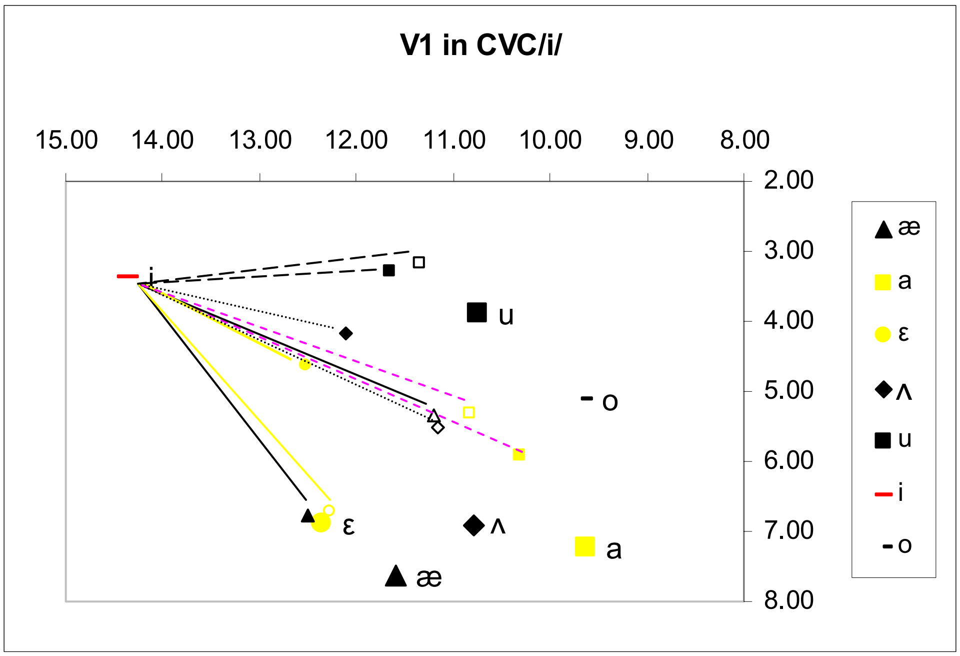

Figure 15 Vowels from high-*R* and low-*R* CVC/i/ words (averaged across items and talkers at the 5ms timepoint), plotted with canonical vowels. Large symbols represent canonical vowels; small symbols represent averaged test vowels; open small symbols represent vowels from high-*R* words and filled symbols represent vowels from low-*R* words. Note that the vowels in low-*R* words are closer to the influencing vowel /i/ than those in high-*R* words.

3.2.2. Carryover (V1 to V2)

For carryover vowel-to-vowel coarticulation, theV2s, which exhibit coarticulatory influence from the V1s, were compared with their canonical counterparts. It is necessary to note that V2 does not carry the main stress in the CVCV test words, while canonical vowels are based on stressed monosyllabic words. In English, stress is described as involving more extreme, rapid articulatory gestures (e.g., Beckman and Edwards, 1994; Cho, 2001), as well as an increase in overall syllable amplitude, pitch, and duration (e.g., Bolinger, 1958; Gay, 1978). So we expect some deviation from canonical even without coarticulation. However, because the difference in the stress exists for both high-*R* and low-*R* test words (the comparison of which is the interest here), it will still be assumed that the difference in deviation from canonical between the two sets of words represents a difference in degree of coarticulation.

3.2.2.1. Distance from canonical

The distances from canonical for the V2 test vowels, pooled across items within each lexical confusability category, were submitted to a three-way repeated measures ANOVA with nested within-subject factors of *R* (High vs. Low), Position (5ms, 10ms, 15ms, 20ms), and Set (CVC/i/, CVC/o/, V-matched). The analysis showed significant main effects for all three factors. The effect for *R* [$F(1,11) = 4.87$, $p = .05$] reflected the fact that V2 was more distant from canonical in low-*R* than in high-*R* words. Fisher's PSLD post-hoc comparisons showed that the effect for Position [$F(1.36,11) = 4.00$, $p = .05$] was a result of the fact that vowels differed more from canonical at the 5ms and 10ms points, closer to the beginning of V2 and nearer the influencing V1, than at the 15ms and 20ms points. The effect of Set [$F(2,11) = 45.65$, $p < .0001$] indicated that the final vowels in CVC/o/s and V-matched words differed more from canonical than the final /i/s in CVC/i/ words. There were no significant interactions in the carryover coarticulation (V2) analysis. These effects in carryover coarticulation test vowels are summarized in Figure 16a-d. Again, sets are graphed separately to simplify the presentation.

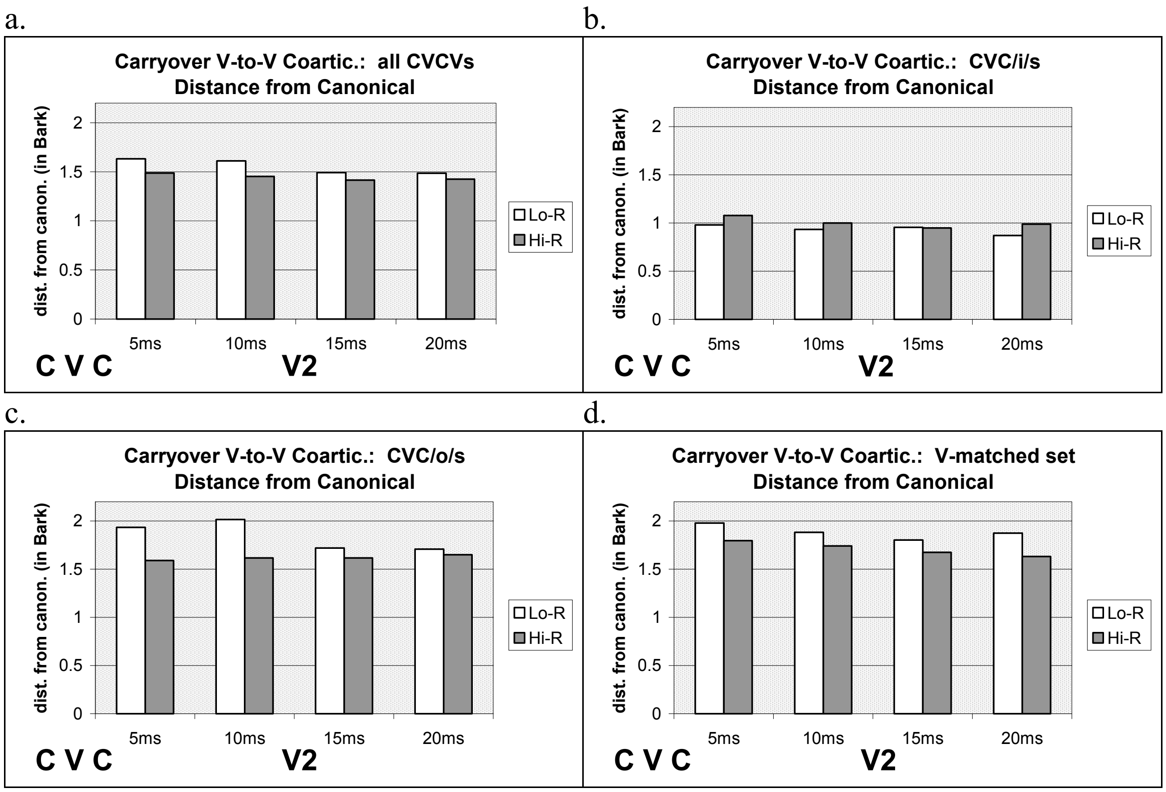

Figure 16 Carryover Vowel-to-Vowel Coarticulation: Distance from Canonical (in Bark) for all CVCVs. Timepoints are again shown in temporal order, this time from 5ms to 20ms. There is a significant effect of *R* overall; any differences across set with respect to the *R* effect are not significant in this analysis.

3.2.2.2. F1 and F2 individual contributions

To investigate the contributions of each formant to the overall effect, mean F1 and F2 differences for each lexical category, pooled across V2s, were also submitted to three-way repeated measures ANOVAs with within-subject factors of *R*, Position, and Set. The analysis for the first formant showed a significant effect of *R* [$F(1,11) = 6.35$, $p = .03$], indicating that V1s in low-*R* CVCV words differ more from canonical than high-*R* words with respect to F1. There was also a significant effect of Position [$F(1.90,11) = 7.27$, $p = .004$], indicating that there was greater F1 deviation in the positions close to the influencing vowel (5ms, 10ms) than in positions further away (15ms, 20ms), according to post-hoc Fisher's PLSD comparisons. There is also one interaction to consider. A significant interaction of Set by Position was found [$F(4.5,11) = 9.08$, $p < .0001$], reflecting the fact that the F2 deviation decreases from 5ms to 20ms for CVC/o/ and V-matched words, while it shows no change across time among CVC/i/s.

Analysis of the second formant revealed no main effect of *R* or any interaction of *R* with other factors. The only significant effects were Set [$F(2,11) = 45.42$, $p < .0001$], indicating to greater F2 deviation for CVC/o/s and V-matched words than for CVC/i/s, and Position [$F(2.61,11) = 5.77$, $p = .005$], due to greater deviation at the 5ms and 10ms points than at the 15ms and 20ms points.

These results indicate that F1 is the primary contributor to the effect of *R* on the degree of carryover vowel-to-vowel coarticulation. In terms of articulation, this means that there was increased carryover vowel-to-vowel coarticulation on the height dimension in hard CVCV words.

3.2.2.3. Distance from opposite V as indication of V-to-V coarticulation

Again, in the interest of verifying that the deviations from canonical were in the predicted acoustic direction for coarticulation, the mean Euclidean distance between the test vowels (V2s) and their opposites (the V1s on the other side of the intervocalic consonant) for each lexical confusability category were submitted to three-way repeated measures ANOVAs with within-subject factors of *R*, Position, and Set. Surprisingly, the analysis revealed no significant effect of *R*. The only significant main effect was for Set [F(1.48,11) = 43.76, p < .0001], where post-hoc Fisher's PLSD comparisons showed that of the final vowels CVCVs, those in CVC/o/s were closest to their cross-consonantal opposites and those in CVC/i/s were furthest away. A significant interaction of Position by Set [F(1.73,11) = 7.63, p = .005] was also found, with post-hoc comparisons indicating that the V2s in CVC/i/s and V-matched words were acoustically closer to the cross-consonantal vowels at timepoints closer to that vowel (i.e., closer from 5ms to 20ms), while there was no such positional pattern for the CVC/o/s.

3.2.3. Comparing Directions of Vowel-to-Vowel Coarticulation

The relative effect of lexical difficulty on the two directions of vowel-to-vowel coarticulation can be examined by means of the V-matched set that was designed precisely for this purpose. And because there was no interaction of Set (CVC/i/, CVC/o/, or V-matched) with *R* for either anticipatory or carryover vowel-to-vowel coarticulation, this comparison should be representative of what the CVCV set as a whole would look like if the two vowels were balanced. Recall that in the V-matched set, the vowels in the V1 position and the vowels in the V2 position were balanced so that the same vowels coarticulate with the same other vowels in both directions.

As in the nasal case, the magnitude of anticipatory vowel-to-vowel coarticulation is greater at its extreme (i.e., closest to the influencing vowel) than the carryover coarticulation. (See Figure 17.) And like in the nasal case, the carryover coarticulation is more steadily maintained throughout the vowel, while anticipatory V-to-V coarticulation increases towards the influencing segment. Because no interaction of Position and *R* was found for either anticipatory or carryover coarticulation, across-position means can be used to represent the overall degree of deviation from canonical in each condition, simplifying the comparison. Though it appears (e.g., in Figure 18) that the magnitude of the difference between high-*R* and low-*R* may be greater for anticipatory (M = .35 Bark) than for carryover (M = .17 Bark) coarticulation, due to cross-speaker variation, a within-speaker paired t-test failed to confirm any difference [t(11) = -1.38, p = .19]. This means as well that there is no reliable difference in the effect of *R* on coarticulation in stressed versus unstressed syllables.

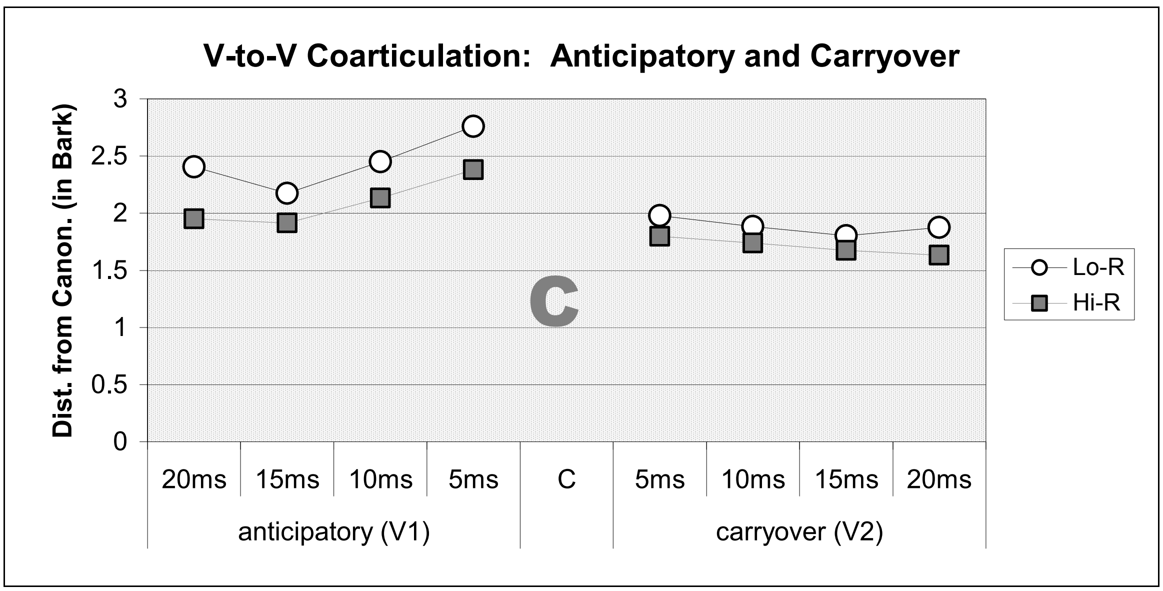

Figure 17 Anticipatory and carryover vowel-to-vowel coarticulation (distance from canonical) across measurement positions.

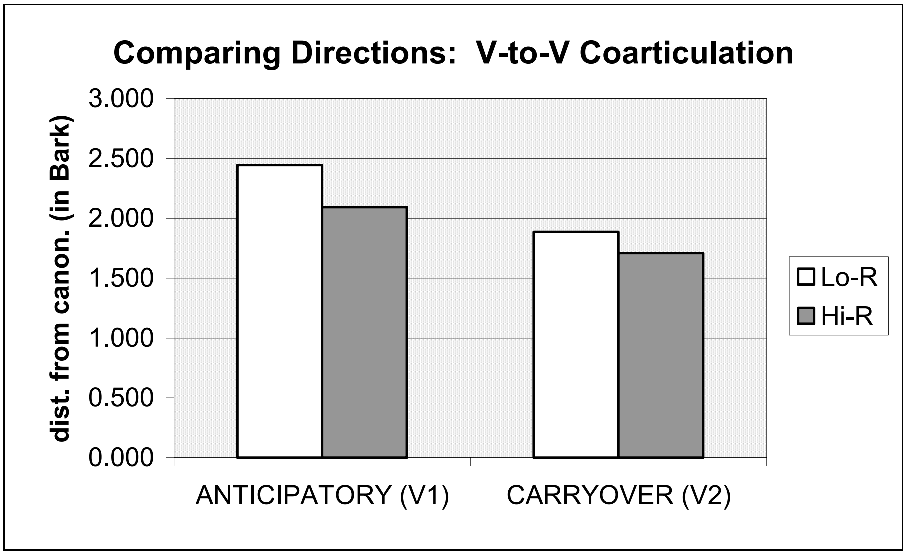

Figure 18 Comparing directions of vowel-to-vowel coarticulation: mean distance from canonical for low-*R* vs. high-*R* CVCV words in the V-matched set.

3.3. Vowel Reduction

3.3.1. Duration

Durations of test vowels were compared across lexical confusability categories for words within each coarticulation and direction set. Means are shown in Table 6 For both V1 and V2 in CVCV words, paired within-subject t-tests showed no significant differences in duration between high-*R* and low-*R* words [V1: $t(11) = .08$, $p = .94$, V2: $t(11) = 1.34$, $p = .21$]. Likewise, for NVC words, there was no effect of lexical category on vowel duration [$t(11) = 1.13$, $p = .28$]. A significant difference in duration between low-*R* and high-*R* words was found, however, among CVNs [$t(11) = -11.45$, $p < .0001$]. Vowels in high-*R* CVNs were shorter than those in low-*R* CVNs. Coda size was considered as a possible confounding factor influencing vowel duration in the CVNs. Vowels before complex codas are known to be shorter than those before simple codas.

And although the number of complex codas was balanced to the extent possible across lexical confusability categories, in fact, there were more complex codas among high-*R* than among low-*R* words. However, the significant difference in duration across *R* categories was maintained in both the simple coda [t(11) = -4.76, p = .0006] and complex coda [t(11) = -5.62, p = .0002] word groups considered separately.

	high-*R*	low-*R*
C**V**CV V1	0.109	0.109
CVC**V** V2	0.167	0.172
NVC	0.177	0.181
CVN	0.159	0.201

Table 6 Mean vowel durations (in seconds) for each group of test vowel

3.3.2. Centralization/Hyperarticulation

The degree of another type of reduction, namely vowel centralization, was also examined in order to verify Wright's (1997; 2004) effect in the current data and to look at the relation between coarticulation and reduction in lexically-mediated speech. Differences in vowel realization at the vowel midpoints, considered to be estimates of the vowel target, were examined, and reduction was measured, as in Wright's study, as a distance from the center of a talker's vowel space.

For the set of all monosyllabic nasal items (both CVNs and NVCs), vowels from low-*R* words were slightly but significantly farther from the center of the vowel space than vowels from high-*R* words. A two-way repeated measures ANOVA with factors of *R* and Nasal Set compared the mean Euclidean distances from the vowel space center for words in each *R* category, showing a significant effect of *R* [F(1,11) = 20.79, p = .0008]. The effect is reflected in both subgroups (the CVNs and the NVCs), as there is no interaction of Set with *R*. A significant effect of Set [F(1,11) = 10.41, p = .008] also indicates that the vowels in the CVNs happen to be more peripheral than those in NVCs. These findings are summarized in Figure 19.

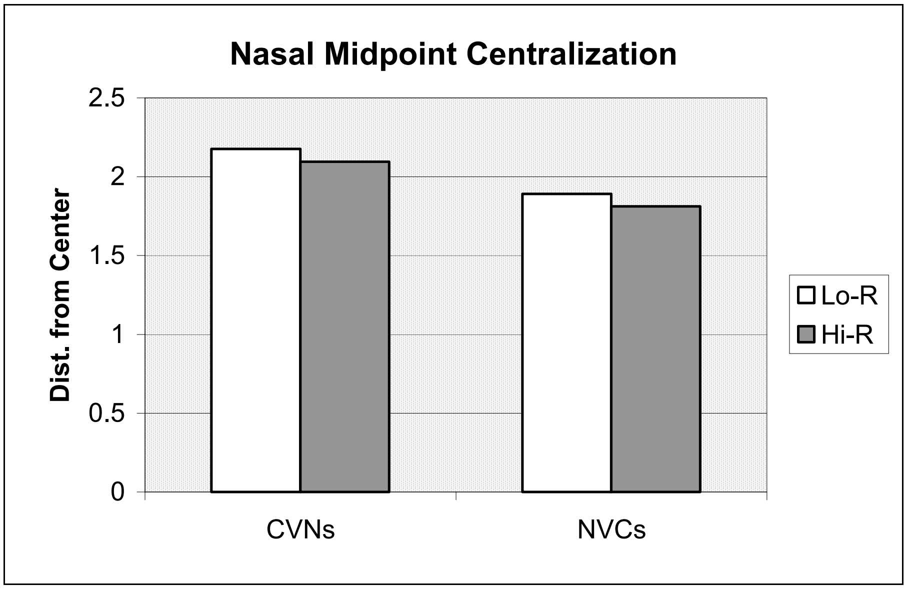

Figure 19 Euclidean distance between nasal vowel midpoints and vowel space center of gravity, averaged across talkers, for low-*R* versus high-*R* words.

For the CVCV words as well, vowels from low-*R* words were farther from the center of the vowel space than those from high-*R* words. The Euclidean distances from vowel to vowel space center were pooled within each *R* category and submitted to two-way repeated measures ANOVAs with factors of *R* (low-*R* and high-*R*) and Set (CVC/i/, CVC/o/, V-matched). For the V1s, the main effect of *R* did not reach significance. However, a *R* by Set interaction was found [F(2,11) = 3.30, p = .05]. T-tests within each Set indicated that V1s in low-*R* words were further from the center of the vowel space for both CVC/i/s and V-matched words, but not for CVC/o/s. For the V2s, there was a main effect of *R* [F(1,11) = 7.54, p = .02] as well as an *R* by Set interaction [F(1.24,11) = 6.26, p = .02]. The significant main finding that low-*R* words have more peripheral V2s than high-*R* words seems to be largely influenced by the CVC/i/ subgroup, which shows the effect, while there is no difference in distance from center for either CVC/o/s or V-matched words, according to Fisher's PLSD post-hoc pairwise comparisons. These effects are summarized in Figure 20.

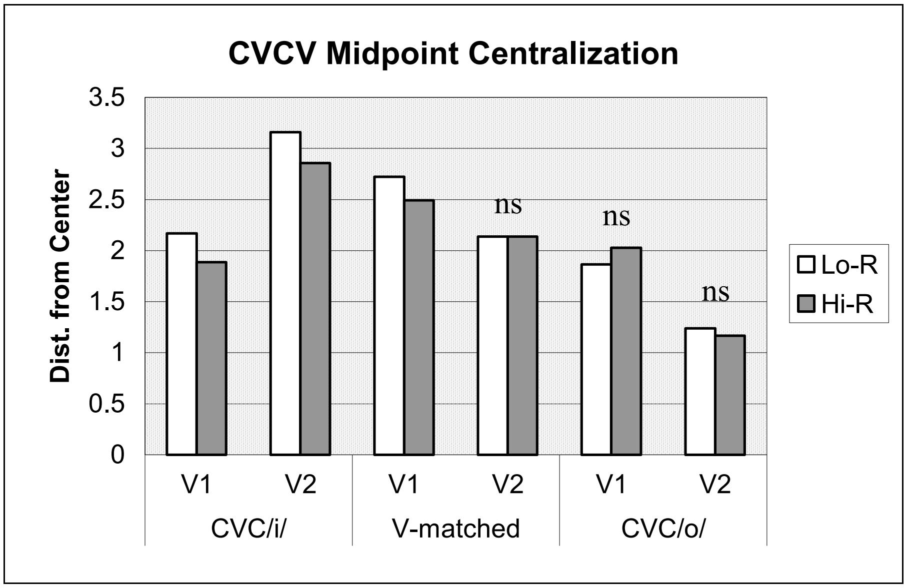

Figure 20 Euclidean distance between CVCV vowel midpoints and vowel space center of gravity for low-*R* versus high-*R* words. 'ns' indicates a non significant comparison.

We can note that there is no vowel expansion effect for V-matched set V2s or for either vowel in the CVC/o/s. The lack of effect for the /o/s of the CVC/o/s is at least partly not unexpected. In Wright's study, point vowels (/i/, /æ/, /ɑ/, /u/) were shown to be further from the vowel space center in "hard" words, but mid vowels showed much less, if any, difference between "easy" and "hard". Thus, the lack of effect for V2 in the CVC/o/s (i.e., /o/) is actually predicted. The distinction between point vowels and others might also account for the lack of effect in certain other cases as well, due to the distribution of vowels in each set. The V2s in the CVC/i/ tokens are naturally all point vowels, as are 70% of the CVC/i/ V1s and 75% of the V-matched set V1s, whereas only 50% of the V1s in CVC/o/s are point vowels. Thus, the centralization effect among the CVC/o/s could be predicted to be weaker than among the first vowels in CVC/i/s or V-matched words. A further mediating factor among the CVC/o/s is the presence of intervocalic liquids in 75% of the words. It is a peculiarity of the lexicon of English that CVC/o/-type words are especially likely to have an /l/ or /r/ in intervocalic position. And the presence of this liquid surely has a strong coarticulatory effect on the adjacent vowels, including of course the V1. The effect of the liquid coarticulation may be strong enough to obscure any centralization that might also (or otherwise) occur.

The difference between V1 (where there is a marginal effect of *R*) and V2 (where there is no effect) in the V-matched set cannot be explained by the identity of the vowels, though, since the vowels in the V1 position are the same as those in the V2 position. The difference might be attributable, however, to stress. The V1s, like the vowels in Wright's monosyllabic test words, are all stressed, whereas the V2s are not. Note that all of the V2s in the V-matched set are less peripheral than the V1s, suggesting that although the final vowels are not phonologically completely reduced (i.e., they do not reduce to schwa), they are somewhat reduced (i.e., centralized) relative to the same vowels in the stressed first syllable position. Stress could contribute to the lack of effect in V1 of CVC/o/s as well.

The data from both the V-to-V and nasal coarticulation test words indicate that vowels in low-*R* words were more peripheral than those in high-*R* words, in accord with

Wright's (1997, 2004) finding that vowels in "hard" (low-*R*) words are less reduced or centralized than those in "easy" (high-*R*) words. It is interesting to note that in the current study, this effect was found in both monosyllabic words (such as those Wright investigated) and in disyllabic forms (in which there is also vowel-to-vowel influence).

3.4. Summary and Local Discussion

3.4.1. Summary of Main Results

To summarize, in the current data, there was consistently greater nasality in low-*R* CVN and NVC words than in high-*R* ones, indicating a greater degree of both anticipatory and carryover nasal coarticulation in harder words. And there was a greater deviation from canonical for both vowels in the low-*R* CVCV words, accompanied, for the V1s, by a closer acoustic proximity to the cross-consonantal vowel, indicating more anticipatory and carryover vowel-to-vowel coarticulation in more confusable words. These effects extended throughout the analyzed portion of each vowel: through the entire vowel in the nasal case, and throughout the 20ms closest to the influencing vowel in the V-to-V case. It is clear then that words with a low relative frequency are produced with *more* coarticulation than less confusable words. Thus both parts of the main hypothesis were borne out: it was shown that lexical factors, namely frequency and neighborhood density combined as relative frequency, do affect the phonetic realization of coarticulation, and that they affect it such that words with a lower relative frequency (low-*R*) are produced with greater coarticulation. The hypothesis that the direction of coarticulation might mediate this effect was not borne out. So far, what we have seen is that the effect of lexical confusability on coarticulation is robust—it occurs across types and directions of coarticulation, and it is temporally extensive. All coarticulation results are summarized in Table 7 and Table 8 below.

	R	Position	interactions
CVN	✓ lo<hi	✓	—
NVC	✓	—	—

Table 7 Summary of nasal coarticulation results. A check mark indicates a significant effect.

	R	Position	Set	interactions	Dist from OtherV
C**V**CV V1	✓ lo>hi	✓	✓	(Pos*Set)	*R*: lo<hi, Pos, Set
CVC**V** V2	✓	✓	✓	—	Set, Pos*Set, (Set*R: CVCi hi<lo)

Table 8 Summary of vowel-to-vowel coarticulation results. A check mark indicates a significant effect. Listed interactions and effects are significant unless otherwise denoted. Parentheses indicate a marginally significant trend.

3.4.2. Carryover Exceptions

Before we continue, the ambiguity of the carryover results, and particularly the CVC/i/ results, deserves some mention. In the main carryover coarticulation analysis (examining distance from canonical), an effect of *R* was found with no *R* by Set interaction. This result indicated that the V2s in low-*R* words were acoustically further from their canonical counterparts than high-*R* words, without regard to what set they were in (which is to say, in the case of carryover coarticulation, without regard to the identity of the vowel (V2)). However, results from two of the supporting analyses did not, in fact, reinforce these findings about coarticulation. Neither the F2 analysis nor the analysis of distance from the influencing vowel showed a significant effect of *R*.

3.4.2.1. Regarding F2 in Carryover Coarticulation

That there was no effect of *R* on F2 for the V2s was consistent with the findings in Brown (2001), which also showed an effect of *R* on F1 difference from canonical in carryover vowel-to-vowel coarticulation, but no effect on F2. There, it was suggested that the apparent lack of effect for F2 might be attributable to the interaction of reduction and coarticulation. Although there were no data on individual formant contributions to reduction in Wright (1997), it was assumed that greater reduction occurred on the F2 (front-back) dimension than on the F1 (height) dimension (since there is more acoustic space between front and back than between any two levels of height). With respect to F2, then, it was hypothesized that the greater centralization in high-*R* words pulled vowels further from canonical, while the increased coarticulation in low-*R* words did the same, causing the two effects to cancel one another out.

Because this story requires that F2 play a greater role in centralization than F1, the relative contributions of F1 and F2 to the centralization effect in the current study were compared. Pooled formant differences from the center of the vowel space for each talker were submitted to a four-way repeated measures ANOVA with factors of *R* (high or low), Set (CVC/i/, CVC/o/, V-match), Formant (F1 or F2), and Vowel (V1 or V2). There was no significant effect of Formant, but a significant interaction of Formant and *R* was found [$F(1,11) = 17.18$, $p = .002$]. Post-hoc comparisons showed the F2 distance from center to be greater in low-*R* words than in high-*R* words, but there was no lexically-conditioned difference for F1 distance from center (as seen in Figure 21a), suggesting that F2 does in fact play a larger role than F1 in centralization in high-*R* words.

In the current study, however, the effect of *R* on F2 was not absent across the board. In the V1 analysis, an effect of *R* on F2 *was* found. In order for the proposed F2 explanation to be plausible, then, there would have to be more centralization in V2s (unstressed vowels) than in V1s (stressed vowels) so that while centralization would cancel out the visible effect of *R* in unstressed V2s, it would not do so in stressed V1s. Although it seems reasonable that there would be more centralization in unstressed vowels than in stressed ones, there was no significant effect of Vowel (V1 or V2) in either the main Distance from Center analysis (with the added factor of Vowel) or the Difference from Center analysis by formant. (Recall that although the V2s are unstressed, the vowels chosen for this position were selected specifically because they did not reduce to schwa under this condition.) However, a significant Formant by Vowel interaction [$F(1,11) = 15.60$, $p < .0001$] shows that there is more F2 contribution to centralization in V2s than in V1s. (See Figure 21b.) Thus, the apparent lack of effect of *R* on F2 in the case of carryover coarticulation can plausibly be explained by the canceling effects of centralization and coarticulation in V2s. The reason for the different relative contributions of F1 and F2 to centralization in stressed and unstressed vowels (as seen in Figure 21b), however, remains unclear.

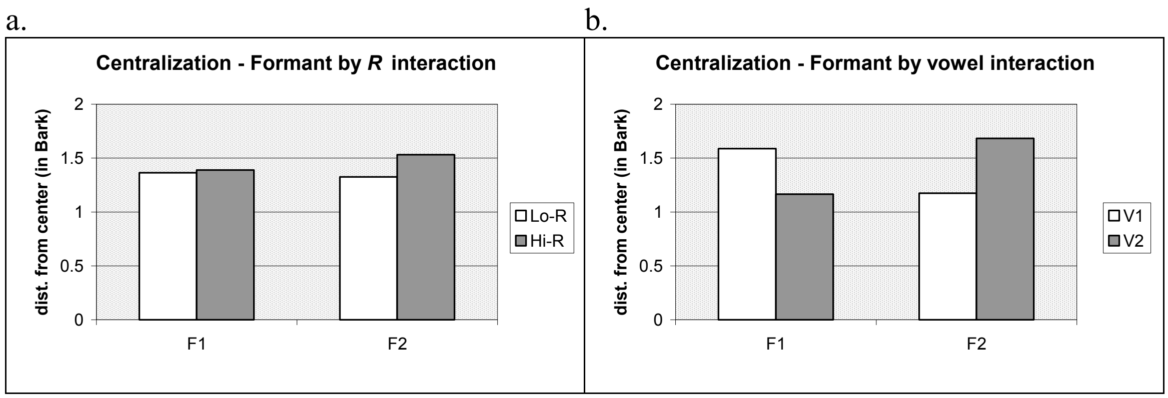

Figure 21 Centralization in CVCVs, by formant

3.4.2.2. Regarding Distance from Influencing Vowel in Carryover Coarticulation

Regarding the distance from influencing vowel analysis, for the V1s, the proximity to the influencing vowel complements the distance from the canonical vowel to demonstrate coarticulation. However, this complementary effect is not present for the V2s. In fact, the analysis even revealed a marginal interaction of *R* by Set [F(1.20,11) = 4.12, p = .06], suggesting that the /i/s in CVC/i/s might actually be acoustically *further* from the influencing V1s in the low-*R* words. The other V2s showed no reliable or marginally reliable pattern. It is not clear what sort of acoustic vowel adjustment is characterized by conflicting Distance from Canonical and Distance from Other Vowel results.

The geometry of the /i/ adjustments is especially puzzling. In the analysis of *F1*, a marginal interaction of *R* by Set was also found [F(1.26,11) = 3.85, p = .06], with a post-hoc two-way ANOVA indicating that theV2s in CVC/i/s did not show the greater F1 deviation in low-*R* words that was seen in the set of V2s as a whole. Without greater F1 or F2 deviation in low-*R* words, and with a tendency for /i/s to be further from the influencing vowel, it is unclear how the /i/ in CVC/i/ words is behaving like other V2s and increasing in degree of coarticulation in the low-*R* condition. And in fact, Figure 16b shows only very small differences between high- and low-*R* CVC/i/ words, as confirmed by the main effect of Set in the carryover Distance from Canonical analysis.

If CVC/i/ words did not share the carryover effect found for the rest of the disyllabic forms, it would not be particularly surprising. /i/ is a stable vowel with a high, extreme tongue position and has been shown elsewhere to be resistant to coarticulation. Such a result was not expected, however, since it was carryover coarticulation onto /i/ for which the lexical confusability effect was found in Brown (2001). Segmental differences between the words used in the two studies, however, could account for these different results: in the earlier study, the low-*R* CVC/i/ words included a disproportionately high number of intervocalic flaps relative to high-*R* CVC/i/s, whereas in the current study, there are relatively few flaps, and they are balanced across lexical categories. Because flaps are so much shorter in duration than other possible intervocalic segments, more vowel overlap could be seen (unobscured by an intervening consonant) in the hard words with the flaps in the first study than in the easy words or in any of the words in the current study.

3.4.3. Relation between the Reduction-Hyperarticulation Effect and the Coarticulation Effect

We have raised the question of what the relation is between reduction and coarticulation, and in particular, between the effect of lexical confusability on reduction, as discussed by Wright (1997, 2004), and its effect on coarticulation, addressed in the current study. We will discuss first the direct physical relation between the two phenomena, and then, in the next section, we will attend to the possible functional relation between the them as well.

In the current study, as in Wright (1997, 2004), vowels from low-*R* words were found to be more peripheral in the vowel space than vowels from high-*R* words. The data in this study expanded on Wright's findings by showing increased distance from the center of the vowel space not only in monosyllabic words (in this case, the CVN and NVC words), but also in disyllabic CVCV words. And in the CVCVs, vowel space expansion was found both for V1 and V2 in at least some subgroup in the data.

Recall that there were two possibilities regarding the direct relation between reduction/hyperarticulation and coarticulation. First was the possibility that more peripheral, or hyperarticulated, vowels would lead to less coarticulation because the hyperarticulation would involve more extreme, but also faster, articulations to yield more distinct segments. The second possibility was that hyperarticulation would lead to more coarticulation because the bigger, more extreme gestures, when produced for all segments in a word, would overlap more. Given that we find both increased hyperarticulation and coarticulation in low-*R* words, the first possibility seems unlikely. However, it is also not yet clear whether hyperarticulation actually leads to coarticulation, or whether the two processes independently co-occur in the same lexical confusability conditions.

It is not critical to make this distinction in order for the phenomenon of this dissertation to be of interest. Even if increased coarticulation in hard words is a direct result of increased hyperarticulation, it is interesting to observe that the hyperarticulation in fact results in increased coarticulation, given that it could have been otherwise. However, the CVCV words provide the means to examine this relation more closely. If hyperarticulation leads to coarticulation, then we should expect hyperarticulation of one vowel to lead to coarticulation with the other vowel (manifested as deviation from canonical in that other vowel). Since there are gaps in the hyperarticulation pattern such that not every vowel is hyperarticulated and coarticulated in every instance (for instance the /o/s do not become more peripheral in CVC/o/s), we can see whether the hyperarticulation and coarticulation patterns interact in the predicted manner across these gaps. Figure 22 summarizes the hyperarticulation/expansion pattern for V1 and V2 on the left and the coarticulation pattern on the right. Effects for opposite vowels (V1 and V2) are shown directly across from one another, while effects for the same vowel are shown diagonally across from one another.

Expansion in CVCi – V2	Coartic. in all CVCV – V1
Expan. in CVCi, Vmatch – V1	Coartic. in CVCo, Vmatch – V2

Figure 22 Expansion and coarticulation patterns for CVCV vowels. Effects for opposite vowels within a word type are shown directly across from one another; effects within the same vowel are shown diagonally across from one another.

Note that the gaps in the patterns do not align perfectly. The top row of the figure shows that we find the coarticulation effect even without the hyperarticulation effect: only /i/ is shown to become more peripheral in V2 position, yet a coarticulation effect is seen in V1s for all word sets. (Likewise, there was coarticulation in the V2s of CVC/o/s without corresponding hyperarticulation of V1s in that set, though the lack of a coarticulation effect in V1 in CVC/o/s was hypothesized to be attributable to the fact that the effect was covered up by coarticulation from the intervening liquid.) Furthermore, there was hyperarticulation that did not yield coarticulation, as in the CVC/i/s where V1 was found to hyperarticulate but V2 did not show coarticulation. (As mentioned above, in the case of the CVC/i/s, we might suppose that no coarticulation is seen on the /i/ due to its own extreme hyperarticulation. We should note at this point, however, that it is not the case that other vowels that hyperarticulate also resist coarticulation. Coarticulation was found in all V1s despite the fact that these vowels were also hyperarticulated in at least the CVC/i/s and V-matched words.)

Thus it appears that although coarticulation and hyperarticulation occur in the same lexical confusability conditions, they are not exactly the same phenomenon. While coarticulation may be reinforced by the hyperarticulation process, coarticulation is increased in hard words even where the influencing vowel is not more peripheral. Figure 23 schematically illustrates increased coarticulation in low-*R* words both accompanied by hyperarticulation and without hyperarticulation.

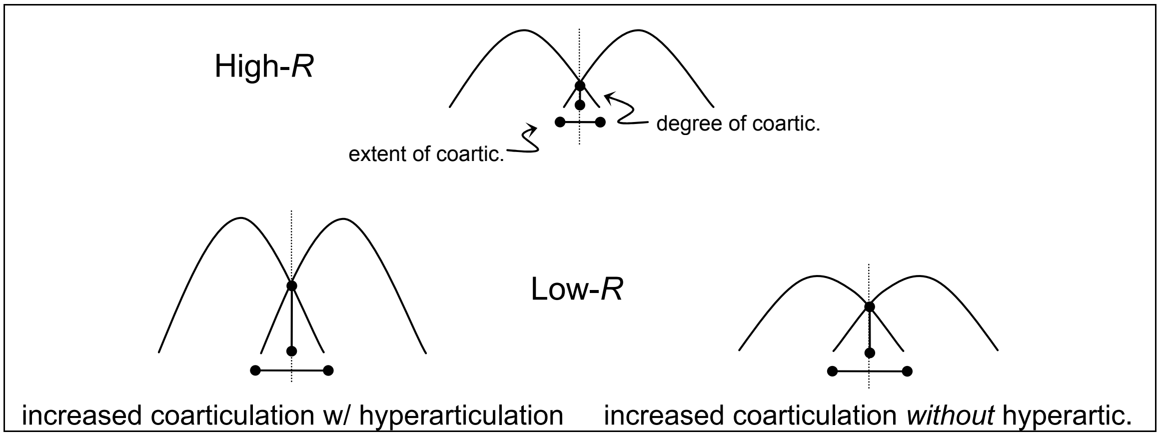

Figure 23 The *R* effect: increased coarticulation in low-*R* words shown both accompanied by hyperarticulation and independently, without hyperarticulation.

3.4.4. Coarticulation Effect as a Communication-Oriented Phenomenon

That coarticulation is increased in hard words, where hyperarticulation effects were also found, supports a view of coarticulation as a type of hyperarticulation (whether or not it is a direct result of the hyperarticulation in low-*R* words (the Wright effect)), rather than as a kind of reduction. The very mention of "hyperarticulation" strongly recommends a functional interpretation of these data as a listener-directed speech accommodation. Lindblom (e.g., 1990) describes speech at the listener-oriented end of the speech spectrum as "hyperspeech". And hyperarticulation, or hyperspeech, is the process invoked in explicitly listener-oriented speech contexts such as are found in clear speech studies: speakers are said to hyperarticulate when they are trying explicitly to speak clearly. Wright construed lexical confusability (in his case, roughly neighborhood density, but similar to our measure of relative frequency) to be a difficulty for the listener that could trigger, word-by-word, acoustic-phonetic speech accommodations in the form of hyperarticulated vowels in especially confusable words.

Accepting Wright's functional interpretation of lexical confusability as a trigger for listener-directed speech, if we assume that speakers are helpful, it follows that the increased coarticulation in hard words is meant to aid listeners as well. By the much cited view of coarticulation as a speaker-oriented phenomenon (aimed at reducing articulatory effort (e.g., Lindblom, 1990)) and specifically detrimental to segmental perception (e.g., Manuel, 1990), however, this interpretation of the current results is quite surprising. Far from hindering lexical perception, this functional view of the effect of lexical confusability on coarticulation suggests that coarticulation in fact likely serves to facilitate perception.

How might coarticulation help? Coarticulation may in some sense, as Lindblom and others suppose, diminish the acoustic distinctiveness of one segment (namely the coarticulation undergoer). But in overlapping segments (or gestures), it also spreads acoustic properties of one segment to another, providing additional cues for the spreading segment (the source of the coarticulation). These acoustic cues from different segments are not merged into a single, ambiguous acoustic stream. Rather, they are all present in the signal and available to listeners to perceive (Mattingly, 1981). Perhaps, then, coarticulation is not actually in conflict with the listener's need to receive clear, distinct acoustic information. If listeners can compensate for coarticulation, as we know they can, attributing the effects of coarticulation to their source (e.g., Manuel, 1995; Beddor and Krakow, 1999; Mann and Repp, 1980; Fowler and Smith, 1986), and if they can use coarticulatory information to identify other portions of the signal, which we also know they can (e.g., Alfonso and Baer, 1982; Repp, 1983; Fowler, 1984; Whalen, 1984;

Beddor and Krakow, 1999), then acoustic enhancement of certain segments by means of increased coarticulation in hard words could be beneficial to listeners in perceiving words. The coarticulation can provide extra cues for the coarticulatory source segment without hurting the cues for the segment on which the coarticulation appears. This account will be further evaluated in the general discussion in Chapter 6.

3.4.5. Direction of coarticulation and lexical effects

Finally we turn to a comparison of the *R* effect across directions of coarticulation. We were interested in the direction of coarticulation based partly on relative potential usefulness of anticipatory and carryover coarticulatory information to the listener given the role of temporal direction hypothesized in certain prominent models of lexical access. The data presented in this chapter indicate, however, that both anticipatory and carryover coarticulation reflect lexical confusability. These data suggest that cues that *follow* a segment may be perceptually useful as well, influencing its identification in lexical recognition. The retrospective use of cues in word perception has been suggested by other studies as well. For instance, Repp (1978) showed that changing the interval of silence between two words can change listeners' percept of the first word. And, quite relevantly, the presence of carryover coarticulatory cues has been shown to speed up lexical recognition (Brown, 2001).

These facts are reflected in other models of lexical access, some of which explicitly allow later segments to affect earlier ones (e.g., Grossberg and Myers, 2000), and some of which (like the Neighborhood Activation Model which serves as the basis for the notion of lexical confusability considered in the current study) simply make no distinctions among segments based on their earlier or later position in a word (e.g., Luce, 1986; Luce and Pisoni, 1998). If later cues, those following a segment, can be used in lexical identification as well, listener-oriented lexical adjustments in coarticulation could involve both the anticipatory and carryover types.

Chapter 4: Phonological Influences—Effects of Lexical Confusability on Nasal Coarticulation in French

We have been exploring the relation between coarticulation and the lexicon. The data presented so far for English have demonstrated that there *is* such a relation, and that it is reasonably robust, seen across several types of coarticulation (nasal and vowel-to-vowel, anticipatory and carryover). We are now in the position to ask whether the relation is robust across *languages*, as well. In developing theories of linguistic phenomena, it is critical to know whether they are specific to certain languages, or whether they are general across a variety of languages, perhaps universal. Although it is impossible in the scope of a single study to make a final determination that any phenomenon is universal, we can reasonably begin by extending the investigation to a second language. In the current study, we will bravely explore the robustness of the effect of lexical factors on the phonetic realization of coarticulation by examining a case in a language in which the effect we have seen for English might not occur. Specifically, the study will investigate the relation between nasal coarticulation and lexical factors in French.

Vowel nasality has a different phonological status in French than it does in English. In French, nasality is phonemically contrastive: there are oral vowels and nasal vowels that differ from oral vowels only (or essentially only) with respect to their nasality. There has been much speculation that the possible phonological contrasts in a language constrain coarticulation. Manuel (1990) (see also Manuel & Krakow, 1984, and Manuel, 1999) hypothesized that the amount of coarticulation that can occur in a language is constrained by the requirement of preserving contrast among the phonemes in the language's inventory. In investigating vowel-to-vowel coarticulation by speakers of three related Bantu languages, two with 5 vowel inventories and one with a 7 vowel inventory, she found less coarticulation for the speakers of the 7 vowel language than for the speakers of either of the two 5 vowel languages. She explained this pattern by claiming that in the 7 vowel language, speakers were relatively limited in their ability to coarticulate because the coarticulation might cause one vowel to spread into the phonetic space of another nearby vowel. In the 5 vowel languages, on the other hand, there was more phonetic space available for each phoneme, permitting a greater degree of phonetic variation from coarticulation without negative perceptual consequences. Essentially, where there are more contrasts to maintain, Manuel predicts that there will be less coarticulation.

Considering the case at hand, the attested presence of nasal coarticulation in French already poses a possible challenge for Manuel's hypothesis since clearly coarticulation-induced vowel nasality could cause a phonemically oral vowel to encroach on the phonetic space of a neighboring phonemically nasal vowel[4]. In French, despite the

[4] In fact, the view of coarticulation that emerges from her hypothesis—one in which coarticulation threatens contrast (and, ultimately, intelligibility) and is controlled by output constraints that limit its ability to do so—is contrary to a view that would allow coarticulation to be increased in hard words, as we saw that it was in English.

fact that vowel nasalization is contrastive, both anticipatory and carryover nasal coarticulation are attested, though there is an appreciable difference between the amounts of anticipatory and carryover nasal coarticulation that are observed. Anticipatory nasal coarticulation is limited to the edge of the vowel, affecting at most one third of its duration, while carryover coarticulation is more extensive (Cohn, 1990). However, the prediction of Manuel's hypothesis is that this degree of coarticulation is at least constrained relative to what would occur if there were no potential contrast. We will not address Manuel's question directly here, though. Rather, we extend her idea somewhat to the phenomenon at hand and investigate whether language-specific phonology, in other words, the system of possible phonological contrasts in a language, interacts with lexical factors in mediating the word-specific degree of coarticulation. If so, the possibility of phonological nasal contrast in French should prevent speakers from increasing the nasalization in the vowels of low-*R* words through increased nasal coarticulation in those words. In fact, if English speakers produce additional nasal coarticulation in order to increase the intelligibility of hard words, then French speakers might even *decrease* nasal coarticulation in hard words since such an adjustment might make the French words less confusable. The primary hypothesis in this dissertation is that lexical factors influence the production of coarticulation, and it is held generally throughout the dissertation. However, the following auxiliary hypothesis is tested in this chapter:

> **Hypothesis 8 (Auxiliary) :** The effect of *R* on nasal coarticulation in French is eliminated or reversed relative to English.

Recall, however, that there are both *nasal-contrastive* and *non-contrastive* vowels in French. The former are oral vowels with phonemically contrastive nasal counterparts; the latter are oral vowels without a nasal counterpart. By including these two vowel groups in the set of French words for each type (VNs and NVs), we can also investigate another way in which lexical effects on coarticulation might be sensitive to phonology, asking whether specific phonological contrasts affect lexical mediation of coarticulation. In other words, we ask whether the fact that there is a specific nasal phone with which the coarticulatorily nasalized vowel could be confused limits the spread of coarticulation in hard words with nasal-contrastive vowels.

The particular patterns of French nasal coarticulation provide an additional possible language-internal contrast constraint for investigation (and pose further challenges for Manuel's hypothesis). The occurrence of nasal vowels adjacent to nasal consonants is restricted in French. Nasal vowels may occur *following* a nasal consonant (e.g., *nain* [nɛ̃] ('dwarf') vs. *nez* [nɛ] ('nose')), but not before a nasal. In other words, vowel nasality is contrastive in the post-nasal position but not pre- nasally. (Incidentally, however, it is carryover nasal coarticulation that is attested to be more extensive in French.) Assuming there is some effect of *R* on coarticulation in French, we will be in the position to test the following auxiliary hypothesis:

> **Hypothesis 9 (Auxiliary):** The degree of nasal coarticulation in French words with non-contrastive vowels is mediated by lexical confusability, while the degree of nasal coarticulation in words with nasal-contrastive vowels is not.

4.1. Nasal Coarticulation

As with the English data, the nasality of the vowels in the words of the French corpus was measured (as described in Chapter 2) and compared across lexical confusability categories. This comparison was made for each vowel group (nasal-contrastive and non-contrastive) for each direction of coarticulation. The spectral measures of nasality (A1-P0 or A1-P1) were made at the onset, midpoint, and end of each vowel. Unfortunately, A1-P0 measures cannot be directly compared to A1-P1 measures, so the amount of coarticulation in the non-contrastive vowel words (measured with A1-P1) cannot be compared with the amount of coarticulation in the nasal-contrastive vowel words or in English. However, the difference between high-*R* and low-*R* words, which is the primary comparison of interest (and the only comparison addressed by the hypotheses stated above), can still be examined.

4.1.1. In Non-contrastive Vowels

We begin with the non-contrastive vowel set because, if the lexical effect is mediated by specific phonological contrasts (but not the more general, language-level type of contrast), this is the group of words that has no limiting contrasts. Therefore, it is the set of words that might be expected to show an effect of *R* on coarticulation (as seen in English) even if the effect is limited in the nasal-contrastive set.

4.1.1.1. Anticipatory (VN)

Low-*R* VN words show slightly larger mean A1-P1 values than high-*R* VNs at all measurement positions. (Recall that A1-P1 values are smaller in more nasal vowels.) However, there is no clear pattern of means for individual subjects. It can be observed, though, that for both individual subjects and pooled across subjects, A1-P1 values are smaller at the end of the vowel than at the beginning or midpoint.

A two-way repeated measures ANOVA with nested within-subject factors of *R* (High vs. Low) and *Position* (Beginning vs. Midpoint vs. End) was performed on the A1-P1 values. There was a significant main effect of Position [$F(1.06,7) = 3.76$, $p = .05$], but no other significant main effects or interactions. There is no reliable difference in nasality, then, between low-*R*, or "hard," words and high-*R*, or "easy," words. With respect to the effect of Position, vowels were more nasal adjacent to the nasal consonant than at either the midpoint or the vowel onset. The mean nasality for all positions and the effect of Position are summarized in the graph in Figure 24.

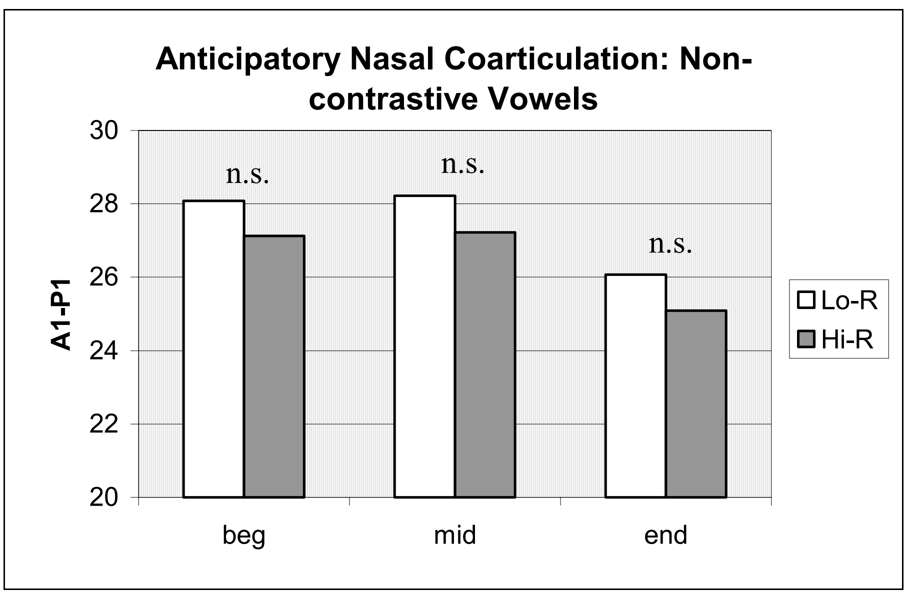

Figure 24 A1-P1 (representing anticipatory nasal coarticulation) in low-*R* vs. high-*R* VN words with non-contrastive vowels. There are no significant differences in nasality between low-*R* words and high-*R* words at any point throughout the vowel.

4.1.1.2. Carryover (NV)

Turning to the carryover coarticulation data, an examination of means shows no clear pattern across subjects or positions. A two-way repeated measures ANOVA with nested within-subject factors of *R* (High vs. Low) and *Position* (Beginning vs. Midpoint vs. End) was performed on the A1-P1 values for the NVs. As in the anticipatory case, the analysis showed no significant main effects or interactions, indicating no difference in nasality between low-*R* and high-*R* words at any position. Mean A1-P1 measures for all positions are summarized in the graph in Figure 25.

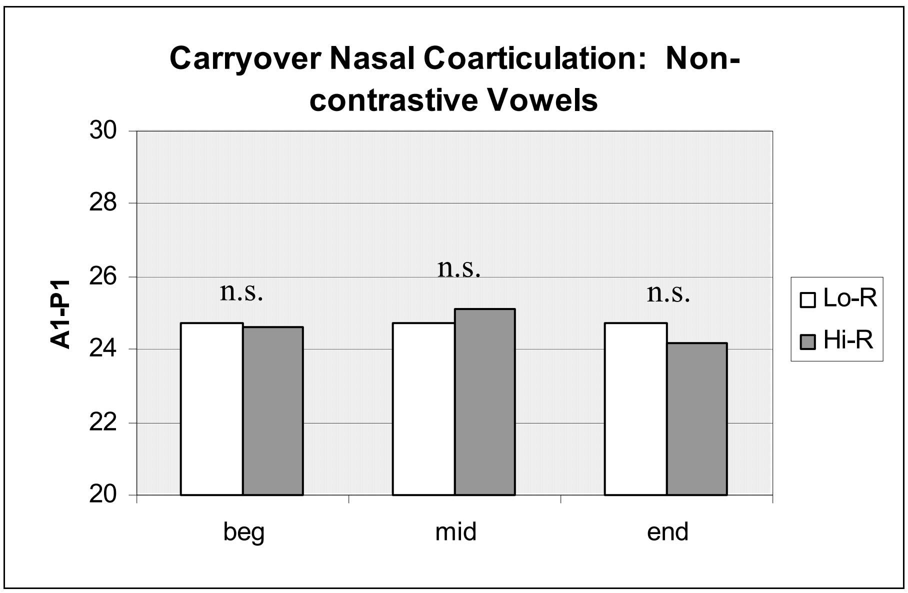

Figure 25 A1-P1 (representing carryover nasal coarticulation) in low-*R* vs. high-*R* NV words with non-contrastive vowels. There are no significant differences in nasality between low-*R* words and high-*R* words at any point throughout the vowel.

4.1.2. In Nasal-contrastive Vowels

Given that no effect was found for *R* among words with vowels that are not contrastive for nasality, where coarticulatory nasality could not lead to perceptual confusion, we approach the analysis of words with nasal-contrastive vowels with less expectation of finding an effect.

4.1.2.1. Anticipatory (VN)

A two-way repeated measures ANOVA with nested within-subject factors of *R* (High vs. Low) and *Position* (Beginning vs. Midpoint vs. End) was performed on the A1-P0 values for nasal-contrastive VN words. There was a highly significant effect of Position [$F(1.46,7) = 46.50$, $p < .0001$], but the effect of *R* failed to reach significance [$F(1,7) = 4.21$, $p = .08$], and there was no *R* by Position interaction. These results indicate that vowels were more nasal adjacent to the nasal consonant than at either the midpoint or the vowel onset. There was no difference in nasality, however, between low-*R*, or "hard," words with nasal-contrastive vowels and high-*R*, or "easy," words. The effect of position on nasality is summarized in the graph in Figure 26. Although graphically this finding for *R* resembles the one for nasal coarticulation in English, the differences are not statistically reliable, making it in fact more like the null finding for the French non-contrastive vowel set.

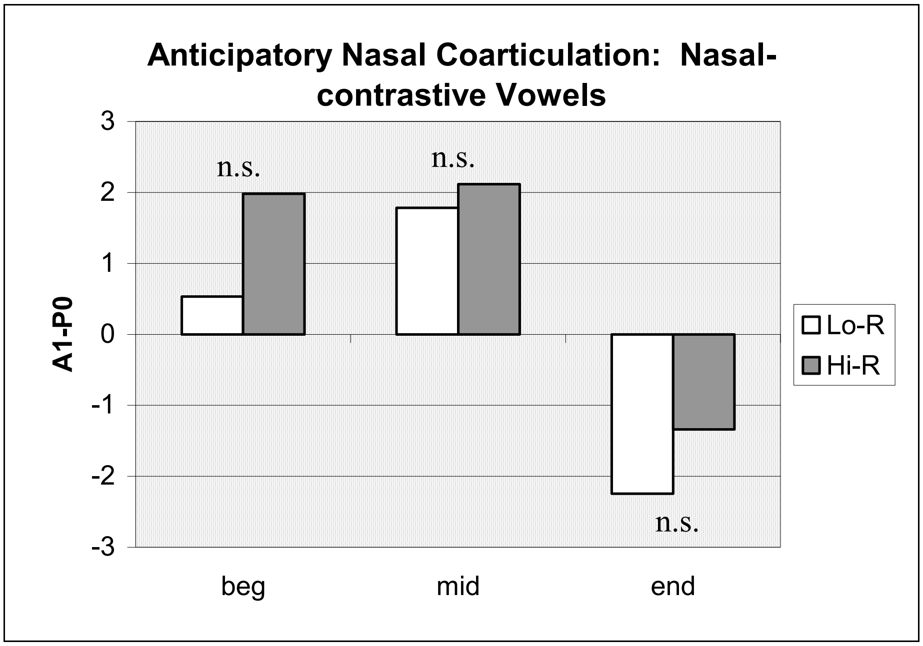

Figure 26 A1-P0 (representing anticipatory nasal coarticulation) in low-*R* vs. high-*R* VN words with nasal-contrastive vowels. There are no significant differences in nasality between low-*R* words and high-*R* words at any point throughout the vowel.

4.1.2.2. Carryover (NV)

Similarly, a two-way repeated measures ANOVA with nested within-subject factors of *R* (High vs. Low) and *Position* (Beginning vs. Midpoint vs. End) was performed on the A1-P0 values for nasal-contrastive NV words. In this analysis, however, there was a main effect of *R* [$F(1,7) = 6.63$, $p = .04$]. The effect of Position failed to reach significance [$F(1.76,7) = 3.56$, $p = .07$], and there was no *R* by Position interaction. These results reflect that low-*R*, or "hard," NV words have more nasalized vowels (i.e., lower A1-P0 values) than high-*R*, or "easy," words throughout the nasal-contrastive vowel. The effect for nasality for all positions is summarized in the graph in Figure 27. These results for carryover coarticulation in nasal-contrastive vowels mirror the English nasal coarticulation results, but not those for the corresponding French non-contrastive vowel word set or the anticipatory French nasal-contrastive set.

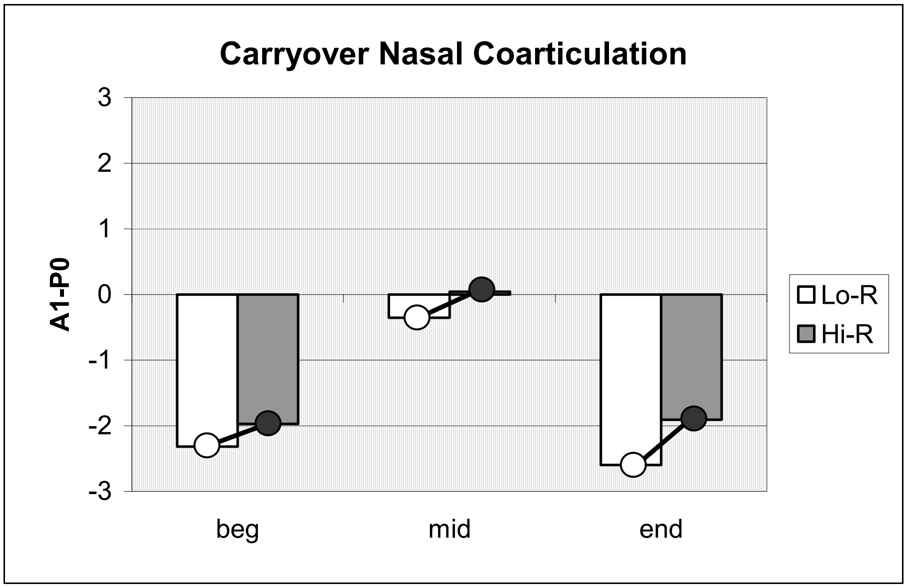

Figure 27 A1-P0 (representing carryover nasal coarticulation) in low-*R* vs. high-*R* NV words with nasal-contrastive vowels. Low-*R* words are more nasal than high-*R* words throughout the vowel.

4.2. Vowel Reduction

4.2.1. Duration

Durations of test vowels were compared across lexical confusability categories for words within each contrast by coarticulatory direction set. For both the VN and NV words with non-contrastive vowels, paired t-tests on talker means revealed no differences in duration between high-*R* and low-*R* words [VN: t(7) = .02, p = .98, NV: t(7) = -1.78, p = .12]. For the VN and NV words with nasal-contrastive vowels, however, there was a difference in duration between high-*R* and low-*R* words. Among VNs, low-*R* words have longer vowel durations than high-*R* words [t(7) = -3.57, p = .01]. For NV nasal-contrastive words, however, high-*R* vowels have longer durations than low-*R* vowels [t(7) = 6.09, p = .0005].

The cause for the differences in duration just among nasal-contrastive vowel words is not clear. Although it is true that hard words have shorter vowels among NVs, which could possibly lead to greater nasal-vowel gestural overlap and contribute to the increased coarticulation, it is also interesting to note that there is much more coarticulation overall in nasal-contrastive NVs than in VNs, even though NVs have significantly longer durations (156ms vs. 127ms, [t(15) = -4.25, p = .0007]).

4.3. Summary and Local Discussion

4.3.1. Summary of Main Results

To summarize, there was greater nasality in low-*R* NVs with nasal-contrastive vowels than in high-*R* words, indicating more carryover nasal coarticulation in harder words, as in English. Among VNs with nasal-contrastive vowels and words with non-contrasting vowels, however, the effects did not match the English data. For the nasal-contrastive VNs and both VNs and NVs with non-contrastive vowels, there was no effect of *R*, indicating that low-*R* words showed no more or less nasality, and thus no more or less nasal coarticulation, than high-*R* words. For both anticipatory coarticulation sets, there was also a significant effect of position, with a greater degree of nasality at the end position adjacent to the nasal consonant than at either the beginning or the midpoint.

4.3.2. *Nasal-contrastive vs. Non-contrastive Vowels*

The specific predictions about the relation between contrastive and non-contrastive vowels and their interaction with lexical effects were not borne out. It was predicted that if nasal contrast, or the potential for contrast, did interact with lexical factors in affecting the degree of nasal coarticulation, it would manifest itself as a constraining or limiting force. In other words, if the existence of contrastive nasality in French interacted with lexical factors, we might see an effect of *R* on nasal coarticulation in English but not in French. Or if contrast played a more fine-tuned role, we might see an effect of *R* on nasal coarticulation even in French, but just on those vowels that do not have nasal counterparts in the French phoneme inventory. But in fact, an effect of *R* on the degree of nasal coarticulation was seen only in one of the sets of words in which it was predicted to be least likely: words (in this case, NVs) with nasal-contrastive vowels. There is no reliable effect of *R* seen among words with non-contrastive vowels.

The existence of an *R* effect on nasal coarticulation in French is not, by itself, particularly surprising (though whether or not it existed was a primary question of this chapter). If the role that lexical confusability plays in mediating the word-specific degree of coarticulation is a completely automatic response to the difficulty of lexical access, then it should occur in French as well as in English. If the effect is rather a modification whose purpose is to increase clarity or intelligibility, then its presence in French might be less strongly predicted (or even predicted to occur in the reverse) if the presence of nasal coarticulation might lead to confusion with phonemically nasal vowels. But if the degree of nasality in vowels nasalized by coarticulation remains distinctly less than the degree of nasality in phonemically nasal vowels in French, there is no reason to assume that French listeners could not take the same advantage of nasal coarticulation cues that English listeners do.

So, is the degree of nasality in the nasalized vowels in French in fact less than the nasality in phonemically nasal vowels? Unfortunately, the design of the current study did not include any phonemically nasal vowels that can be straightforwardly compared. Chen (1997), in her evaluation of the acoustic measures of nasality used in this study, does report A1-P0 values for nasal vowels in French, but she does not measure the nasality in phonemically oral nasalized French vowels. However, we can make a rough comparison between her data on nasal vowels for her talkers and the data on nasalized vowels for the talkers in the current study, bearing in mind that nasality varies quite a bit across talkers, so the comparison is far from perfect. If we examine the measurements from the point Chen identifies as the "most-nasal" and those from the most nasal point in the current study (the beginning of NV vowels in low-*R* words), we can see that nasal vowels are, in fact, more nasalized than coarticulatorily nasalized vowels. The means and ranges, pooled across vowels and talkers, are summarized in Table 9. Because one of Chen's talkers, JS, was far less nasal across the board than any of her other talkers or any of the talkers in the current study (mean A1-P0: 4.85 dB), two sets of values are shown for her data: one for all 8 talkers, and one for the 7 talkers excluding JS. Note that the magnitude of the nasality of phonemically nasal vowels is nearly twice that of the nasalized vowels. Therefore, although no information about the perception of these vowels is available, it is not implausible to suppose that sufficient distinctiveness is maintained between phonemically nasal and coarticulatorily nasalized vowels to avoid confusion.

	A1-P0	
	mean	range
Nasalized vowels (current study)	-2.5 dB	0.37 to -4.67 dB
Nasal vowels (Chen)	-3.5 dB	4.85 to -9.67 dB
Nasal vowels – w/out JS (Chen)	-4.7 dB	-0.75 to -9.67 dB

Table 9 Mean A1-P0 and range for coarticulatorily nasalized and phonemically nasal French vowels, pooled across talkers, vowels. Nasalized vowel data is from the current study; nasal vowel data is from Chen, 1997.

Given these results, however, it is the lack of an *R* effect for the nasal-contrastive VNs and the non-contrastive vowel words that are the findings requiring more explanation. The non-contrastive vowel words will be discussed first, and a discussion of the nasal-contrastive VNs will follow in section 4.3.3.

Not only did our reasoning about the role of contrast lead us to the prediction that, if only certain French words would show an *R* effect, it would be the non-contrastive vowel words, but so did the English findings. With respect to their phonological status, the non-contrastive vowels of French are most like the English vowels, which also have no nasal counterpart. So the role of contrast aside, we are still left with the question of why the French non-contrastive vowels do not behave more like English vowels (showing an effect of *R* on the degree of nasal coarticulation).

It might provide some insight to further consider the very fact that these vowels are not contrastive in the first place in a language with a nasal contrast and to ask why.

Recall that these non-contrastive vowels also have in common that they are all high (/i/, /y/, and /u/). Unfortunately, although this fact may hold the key to making sense of the coarticulatory patterns in the data, it also poses some hindrances to discovering the answer. Because they are high vowels, the appropriate acoustic measure of nasality was A1-P1, while the measure used for the nasal-contrastive French vowels and the English vowels was A1-P0. Direct comparisons of the degree of nasality across French sets or across languages for this set, then, could not be made. However, it is generally the case that high vowels are less nasal than non-high vowels (e.g., Chen, 1997).

From a physiological point of view, nasality may be difficult to produce and control for high vowels. High tongue position and high velum position are correlated, as are low tongue and low velum, due to a physical coupling of the two articulators through the palatoglossus muscle (Dickson & Maue-Dickson, 1980). So not only does nasalization on high vowels require opposing movements of the tongue and velum, but it also requires greater change in velar height than for a lower vowel to achieve sufficient velopharyngeal opening. Therefore, the same physiological constraint that may contribute to the fact that there are no phonemically nasal high vowels in French may also limit speakers' ability to adjust the degree of nasal coarticulation in these vowels, increasing the nasality in low-*R* words.

The dispreference for high nasal or nasalized vowels is reflected in historical phonological development as well. High vowels tend to denasalize earlier than non-high vowels (while low vowels tend to become distinctively nasal earlier than non-low vowels) (e.g., Ferguson, 1975; Ruhlen, 1975). These facts are in accordance with the perceptual fact that low vowels are perceived as more nasal than high vowels in the same contexts (e.g., Ali, et al., 1971; see Beddor, 1994 for discussion).

An explanation incorporating some of these facts could be given from a synchronic phonological point of view as well. The preference against high nasal or nasalized vowels might result from a very highly ranked gradient constraint against high nasal vowels—one that specifies, for instance, that high vowels should be maximally oral, or at least *x* degree oral (where that degree is specified quantitatively). The motivation for such a constraint could be either physiological or perceptual. Under this account, the high vowels could not be more nasalized in hard words because they would simply be constrained not to be any more nasal at all. In fact, one could even imagine that in hard words, talkers might obey this constraint even more strenuously, leading to the near opposite *R* pattern that we see for non-contrastive vowel VN words (where low-*R* words tend to have slightly *less* nasal vowels than high-*R* words).

The data presented in this chapter perhaps leave unanswered part of our original question about role of contrast in influencing lexical effects on coarticulation. But they do show ways that contrast does not play an apparent role. Neither the potential for a particular type of contrast in a language nor even the potential for a specific phonemic confusion (to the extent that nasality from nasal coarticulation might, in fact, lead to possible confusion with nasal vowels) completely limits the increased coarticulation seen in low-*R*, or hard, words, as evidenced by an effect of *R* for NV words with nasal-contrastive vowels. And with the unexpected non-contrastive vowel result, the data additionally indicate a different way in which phonological factors might in fact interact with *R*, suggesting an analysis in which the *R* effect is mediated or eliminated in the non-contrastive words by a dominant constraint against nasality in high vowels.

4.3.3. Direction of Coarticulation and Position of Contrast

What accounts then for the difference between the nasal-contrastive VNs, which also showed no effect of *R* on coarticulation, and the nasal-contrastive NVs, which did? Recall that nasal contrast in French is also positionally constrained: the phonotactics of French prohibit phonemically nasal vowels before a nasal consonant but not after, as illustrated in Figure 28. In other words, the vowel position following a nasal consonant is potentially contrastive for nasality, but the pre-nasal position cannot bear nasal contrast. Therefore, anticipatory nasal coarticulation in French *always* involves a *non*-contrastive vowel, regardless of its quality and its contrastive status in other contexts. Carryover coarticulation, on the other hand, may or may not involve a contrastive vowel, depending on the vowel's inherent phonetic quality. The fact that an effect of *R* was found for carryover, but not anticipatory, coarticulation (among the nasal-contrastive vowel set) suggests that the lexical effect is sensitive to this positional contrast factor.

VN	NV
*ṼN	NṼ

Figure 28 Pattern of permissible vowel – nasal consonant sequences in French. Nasal vowels may occur following but not preceding a nasal consonant.

As in the non-contrastive vowel words, the lexical effect on anticipatory nasal coarticulation in nasal-contrastive words seems to be limited in an environment in which nasal contrast in general is limited. In French, there is no nasal contrast among high (‘non-contrastive’) vowels, and no nasal contrast before nasal consonants. Therefore, the two cases can also be analyzed in a similar manner. Whatever the highly-ranked constraint that prohibits pre-nasal nasal vowels in French—for instance, one that stipulates that vowels should be at least *x* degree oral before a nasal consonant—it also limits coarticulatory nasality in that environment. And in fact, in accord with the patterns Cohn (1990) found looking at airflow data, the current data show less coarticulation in VNs than in NVs for both the nasal-contrastive and non-contrastive word sets. As a point of description, NVs showed nasality throughout the duration of the vowel, while VNs were most nasal at the end measurement point, and interestingly, the nasality at the end of VN vowels is approximately the same as the nasality in NV vowels throughout.

Despite the fact that the effect of *R* was only found in a subset of the data, the French data further demonstrate the robustness of the effect of lexical factors on the production of coarticulation. Lexical effects have now been shown in two languages (and in both, words with a low relative frequency have shown a greater degree of coarticulation). And in French, they have been shown to persist in at least some contexts even though the nasal coarticulation introduces an acoustic cue that is the basis for a phonemic contrast. The effect therefore seems to be largely insensitive to confusability factors that might be predicted to mediate an intelligibility-motivated effect. However, the effect does seem to show sensitivity to structural constraints in the phonological grammar.

Chapter 5: Sublexical Specificity of Lexical Confusability Effects

Whereas the focus of Chapter 4 was on the role of phonological contrasts in a language in mediating lexical effects on coarticulation, in this chapter, the focus is on lexical or sublexical contrasts within a neighborhood and their interaction with *R*. A critical step in building an understanding of the effects of lexical confusability and in shaping the inferences about coarticulation that can be drawn from the current study is characterizing more specifically what kinds of lexical—or sublexical—information these adjustments are sensitive to. On the one hand, the coarticulatory adjustments in low-*R* words might be general, applying to any potentially confusable words. In such a case, all low-*R* words would be predicted to have more of all types of coarticulation. In this scenario, the segments could be thought of as team players: all segments contribute as much as they can to the overall intelligibility of a potentially confusable word by means of spreading coarticulatory cues. On the other hand, the adjustments might be more fine-tuned, or sensitive to the specific ways that the particular neighbors of a given word make that word confusable. In such a case, only the segments critical for distinguishing one word from a competitor word are affected. Here, each segment is on its own to ensure that it at least does not hinder the correct identification of a confusable target word.

The fact that an effect has been consistently found even before the locus of confusability has been controlled for suggests the first option, but the second option has yet to be explicitly tested. For the purpose of addressing this question, let us assume for the moment that adjustments made in low-*R* words have the purpose of reducing the likelihood that those words will be misperceived. In the case of coarticulatory adjustments, we assume that coarticulation is increased in low-*R* words in order to spread segmental cues that facilitate lexical perception. If this coarticulation effect is based on a segment-sensitive type of confusability, then we hypothesize the following:

> **Hypothesis 10 :** Those segments that lead to possible confusion within a neighborhood coarticulate more than segments that do not lead to specific confusions.

So, for example, if a word, CVN, has many neighbors that differ by only the last segment, then the last segment, N, would be predicted to coarticulate in order to expand its cues and increase its likelihood of being correctly perceived.

However, coarticulation involves not only a *source segment* that may spread its cues, but also a *target segment* on which those coarticulatory cues are realized. The acoustic “needs” of the source and the target, then, may conflict. If, as a consequence of the coarticulatory spreading of the source segment, the distinctiveness of the target segment is diminished, confusability by the *target* might lead to coarticulatory resistance, as stated in the following hypothesis:

> **Hypothesis 11 :** Segments that lead to possible confusion within a neighborhood show less influence from the coarticulation of other segments than those segments that play little role in specific confusions.

So, if a CVN word has many neighbors that differ only by the vowel, then the vowel would be predicted to resist coarticulation from the nasal in order to maintain acoustic distinctiveness.

To investigate the individual segmental contributions to lexical confusability accommodations, the set of low-*R* and high-*R* CVN words in the main English corpus was designed to have four sub-categories of words, crossed with respect to their confusability, high or low, by N (the source) and by V (the target). As described in Chapter 2, the degree of anticipatory nasal coarticulation (measured as the amount of nasality) was compared across these more specific confusability categories.

5.1. Speech Materials

5.1.1. Calculating Segmental Confusability

Segmental confusability was calculated as the percentage of neighbors (weighted by frequency) that differ from the target word only with respect to that segment. In the case of the CVN words, then, confusability by N refers to the frequency-weighted percentage of neighbors that differ from the target word only with respect to the nasal (i.e., the presence or absence of a nasal[5]):

$$\text{Confusability by N} = \frac{\Sigma \text{ logfreq}_{\text{neigh conf by N}}}{\Sigma \text{ logfreq}_{\text{all neigh}}}$$

[5] Because nasal coarticulation provides cues only to the fact that the source segment is a nasal and provides no information regarding the segment's place of articulation, it can only serve to increase the intelligibility of the target word relative to neighbors with a non-nasal segment in the corresponding position.

Confusability by V was similarly calculated as the frequency-weighted percentage of neighbors confusable by V (in this case, by phonemic vowel quality).

In principle, words were considered to have a high confusability by N (to be 'hi N') if ≥33% of its neighbors were confusable with respect to the nasal. Likewise, a word was considered to be 'hi V' if ≥ 33% of its neighbors were confusable with respect to the vowel. This would mean that, assuming a CVN-type word with three segments, the nasal or the vowel contributed more than its equal predicted share to the confusability of the target word. Words were considered to have a low confusability by N or by V (to be 'lo N' or 'lo V') if ≤10% were confusable by the critical segment.

In fact, however, due to limits on available test words, hi N confusability ranged from 29 to 74% (M = 39%) and hi V confusability ranged from 26% to 73% (M = 39%), while lo N confusability ranged from 0 to 13% (M = 3%) and lo V confusability ranged from 0 to 14% (M = 3%).

5.1.2. Segmental Confusability Sub-Corpus

This sub-corpus included the 48 monosyllabic words with nasal codas (CVNs) from the main corpus. Twenty-four of the words were high-*R* (easy), and 24 were low-*R* (hard). Within each main lexical confusability group, half of the words were highly confusable by N and half were not very confusable by N; additionally, half of the words were highly confusable by V and half were not. These categories were crossed within each main lexical confusability category to yield four sets of low-*R* words and four sets of high-*R* words, as illustrated in Figure 29. Mean confusability scores, broken down by subset, are shown in Table 10.

		Confusability by N	
		LO	HI
Conf. by V	LO	lo N, lo V 6 high-*R*, 6 low-*R* e.g., **plank**, *rank*	hi N, lo V 6 high-*R*, 6 low-*R* e.g., **stem**, *bran*
	HI	lo N, hi V 6 high-*R*, 6 low-*R* e.g., **romp**, *punt*	hi N, hi V 6 high-*R*, 6 low-*R* e.g., **crunch**, *bum*

Figure 29 Structure of the confusability sub-corpus. Each cell represents 12 words: 6 high-*R* and 6 low-*R*. Example high-*R* words are shown in bold type; low-*R* words are in *italics*.

			Lo Conf. by N		Hi Conf. by N	
			N conf	V conf	N conf	V conf
Conf by V	Lo	Low-*R*	5 %	4 %	38 %	7 %
		High-*R*	0 %	2 %	39 %	0 %
	Hi	Low-*R*	6 %	43 %	33 %	34 %
		High-*R*	1 %	45 %	47 %	34 %

Table 10 Mean segmental confusability for low-*R* and high-*R* words in the segmental confusability sub-corpus.

As in the main corpus as a whole, all words were of equally high familiarity (6.0-7.0 on the 7-point Hoosier Mental Lexicon scale). And overall frequency and segmental context were balanced across lo N/V and hi N/V conditions, as well as across low-*R* and high-*R* conditions. The mean log frequency and the mean and range of *R* values for words in each CVN sub-category are listed in Table 11. Log frequencies, neighborhood densities, and relative frequencies of individual CVN test words can be found in Appendix 1.

		Lo Conf. by N			Hi Conf. by N		
		log freq.	*R*	*R* range	log freq.	*R*	*R* range
Conf by V: Lo	Low-*R*	2.31	.06	.037 - .085	2.33	.05	.028 - .077
	High-*R*	2.44	.22	.149 - .301	2.45	.25	.130 - .323
Conf by V: Hi	Low-*R*	2.48	.07	.058 - .087	2.12	.06	.030 - .084
	High-*R*	2.45	.21	.156 - .280	2.36	.15	.125 - .211

Table 11 Mean Log Frequency, Mean Log Relative Frequency (*R*), and *R* range for nasal coarticulation test words

5.2. Results

Recall the main result for this set of words reported in Chapter 3: there is significantly *more* nasal coarticulation (as evidenced by greater vowel nasality) in low-*R* CVN words than in high-*R* ones overall. Given that this general result obtains when confusability by the nasal and by the vowel were counterbalanced in the set of words, it seems unlikely that a more specific type of confusability is playing a role in this speech production phenomenon. However, a statistical analysis was performed to verify this inference and to examine the possible more complicated interactions among factors.

5.2.1. Main Results (review)

A four-way repeated measures ANOVA with nested factors of *R* (high-*R* or low-*R*), Confusability-by-V (hi or lo), Confusability-by-N (hi or lo), Position (beginning, middle, or end of vowel), and all interactions was performed on mean A1-P0 data. As reported in Chapter 3, *R* was a significant predictor of nasality [$F(1,11) = 6.39$, $p = .03$], with low-*R* words showing smaller A1-P0 values (i.e., greater nasality) than high-*R* words. There was also a significant effect of Position [$F(1.27,11) = 26.18$, $p < .0001$], with the end of the vowel being more nasal than the midpoint, which was more nasal than the beginning.

5.2.2. Confusability by N

There was no effect of Confusability-by-N on the degree of coarticulation. In other words, words confusable by their coda nasal consonant (hi N) do not have reliably more (or less) anticipatory nasal coarticulation than those that are *not* confusable by N (lo N). Furthermore, there was no reliable interaction of Confusability-by-N and *R* (high-*R* vs. low-*R*), indicating that this same lack of effect exists among both low-*R* and high-*R* words. There was, however, a significant Confusability-by-N by *R* by Position interaction [$F(2,11) = 11.87$, $p < .0001$], as shown in Figure 30, representing the fact that the overall effect of *R* is neutralized in two comparisons: at the beginning of the vowel in low nasal confusability words and at the vowel midpoint in high nasal confusability words. At the end, closest to the nasal consonant, where the overall coarticulation is greatest, the *R* effect was seen consistently across N confusability categories.

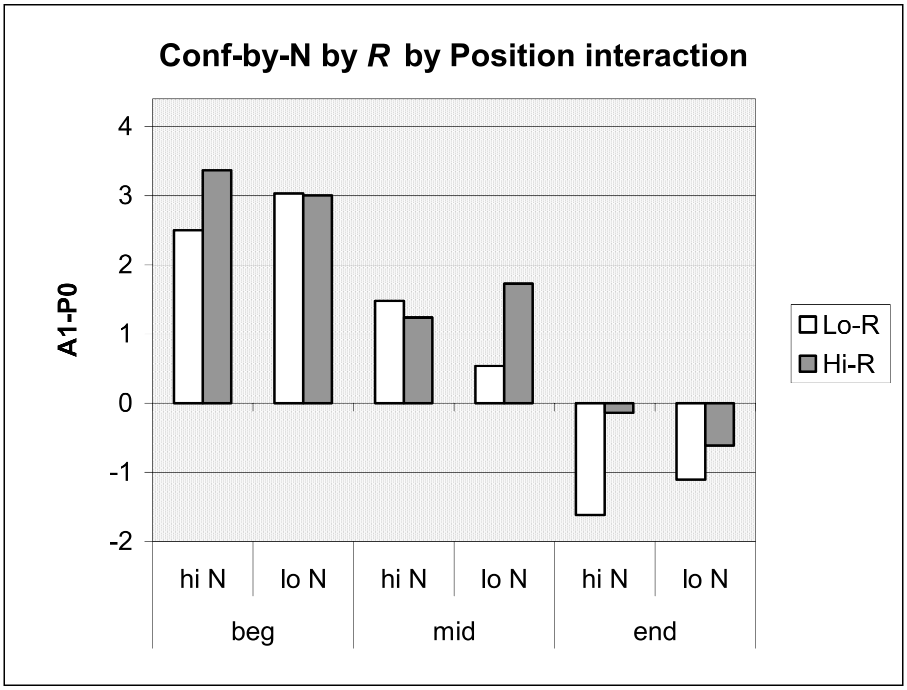

Figure 30 Confusability-by-N by *R* by Position interaction

5.2.3. Confusability by V

The results for Confusability by V are quite parallel to those for nasal confusability. Again, there was no main effect of the segment confusability factor on the degree of nasal coarticulation. Words that were highly confusable by the vowel (hi V) showed no less coarticulation than those that were *not* confusable by V (lo V). And again, there was no reliable interaction of Confusability-by-V and *R* (high-*R* vs. low-*R*). But there was a three-way interaction of Confusability-by-V by *R* by Position interaction [F(1.25,11) = 5.27, p = .03], as shown in Figure 31, representing the fact that at the beginning of low confusability vowels, the *R* effect was unexpectedly reversed such that low-*R* words have slightly higher A1-P0 values than high-*R* words in this one case.

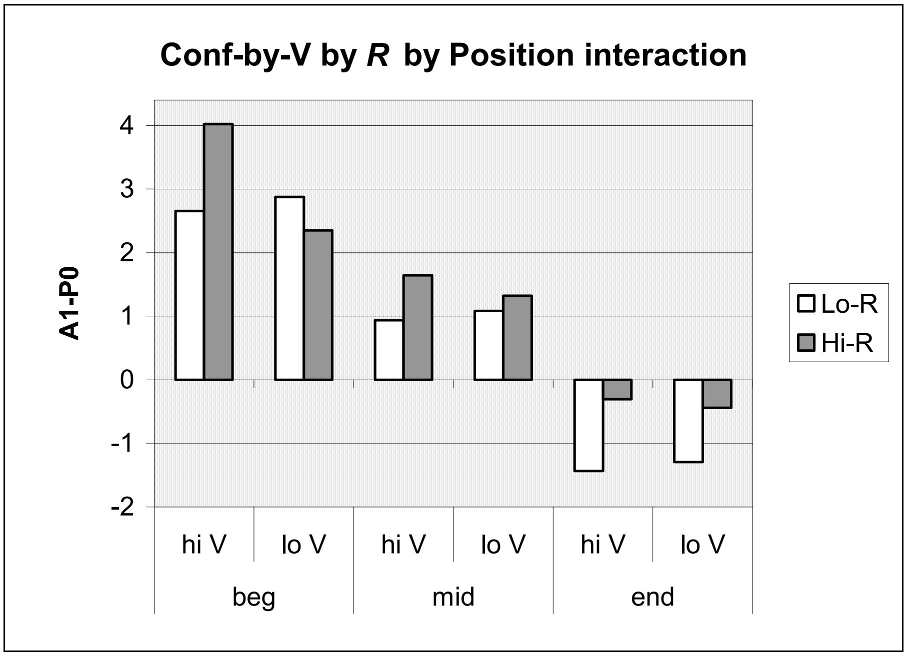

Figure 31 Confusability-by-V by *R* by Position interaction

5.2.4. Relation between Nasal and Vowel Confusability

The interaction of Confusability-by-N and Confusability-by-V is also of interest, as such an interaction could indicate that, regardless of lexical confusability (due to frequency and neighborhood density), one type of segment-specific confusability could constrain the accommodations that might be made in response to another type of confusability. Or put in different terms, the overall confusability that can lead to accommodations in speech production might crucially be based on the interaction of the effects of individual segments. In the current analysis, though, there was not a significant interaction of these two segmental confusability factors. There was, however, a significant interaction of Position by N-Confusability by V-Confusability [$F(2,11) = 24.29$, $p < .0001$], shown in Figure 32, reflecting the fact that N-Confusability and V-

Confusability interact differently at the midpoint and end positions than they do at the beginning. At no position, though, is the interpretation of the pattern immediately transparent.

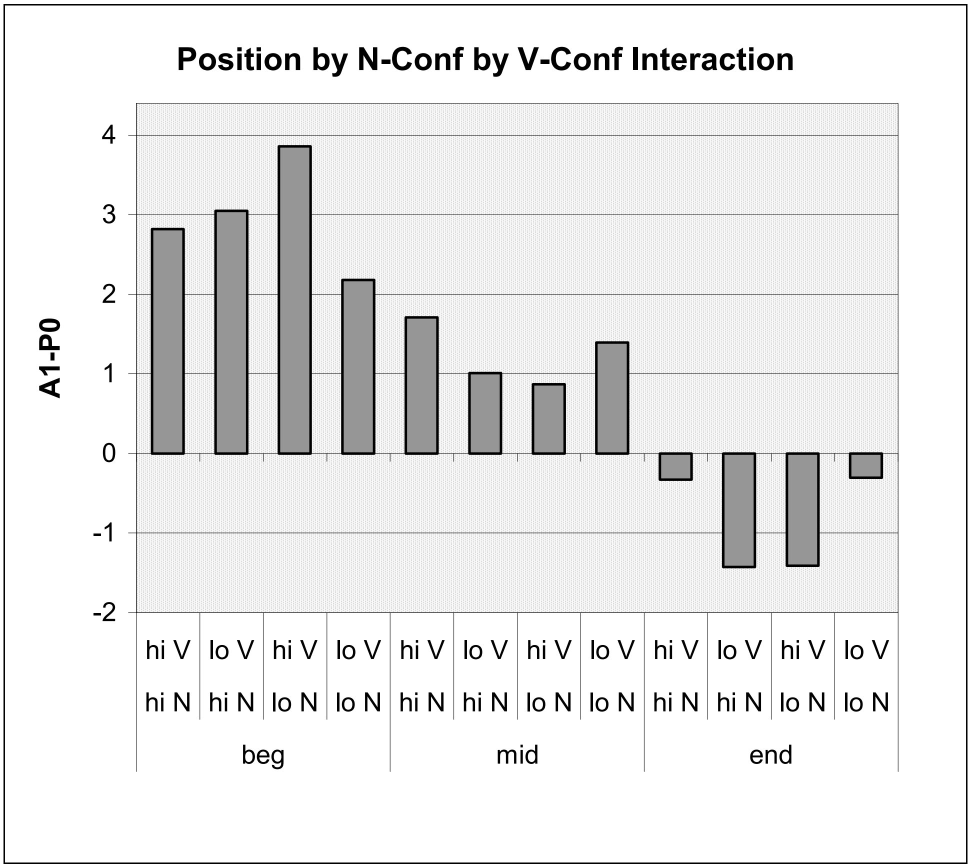

Figure 32 Position by Confusability-by-N by Confusability-by-V interaction

5.3. Local Summary and Discussion

As was shown in Chapter 3 and again in this chapter, there is *more* anticipatory nasal coarticulation in low-*R* (hard) words than in high-*R* (easy) ones overall. And this effect exists regardless of the individual contribution of either N or V to the overall confusability of a word. Low-*R* words that are *not* confusable by their nasal show as much increase in coarticulation as low-*R* words that are highly confusable by the nasal, relative to high-*R* words. And confusability by the vowel does not mediate this effect. We can infer, then, that specific confusability within a neighborhood does not interact with *R* in influencing lexical adjustments of coarticulation. And because confusability by a particular segment is not necessary to induce coarticulatory adjustments of that segment, we can conclude that accommodations to lexical confusability occur at the whole-word level rather than sublexically.

These results, along with the results presented earlier in this dissertation, indicate that speakers are able to (or perhaps are constrained to) take potential lexical confusability into account in the phonetic implementation of coarticulation. They produce *more* coarticulation in low-*R* ("hard") words. And to do this, they both keep track of and have access to, in some capacity—perhaps by explicit representation or perhaps in virtue of the difficulty of their own lexical access in speech production—a very large amount of information about the lexicon, including frequencies or relative frequencies and phonological neighborhoods. But, there are clearly limits to the specificity of the lexical facts that speakers can access and/or the adjustments they make. Speakers do not, or perhaps cannot, use as much lexical information as we might imagine they could.

These findings add to a small, but seemingly growing, body of data that suggests that lexical factors have very general effects on speech production (despite more specific effects on lexical perception). Goldinger and Summers (1989), for instance, compared the VOT difference in voiced-voiceless minimal pairs from dense and sparse lexical neighborhoods. They found more difference for pairs from dense lexical neighborhoods than from sparse ones, even though in every pair there was exactly one neighbor that differed with respect to VOT, and in no case could there even possibly be more than one such confusable neighbor. Therefore, speakers' calculation of confusability or their use of this information in speech implementation seems not to be sensitive to single features (e.g., voicing). In a more explicit testing of the level at which lexical factors influence speech production, Billerey (2000) compared the degree of vowel reduction (found by Wright (1997) to occur to a greater degree in "easy" words) before and after a word's uniqueness point, with the idea that words should be similarly easier *after* their uniqueness point than before. However, he found no evidence for a difference in vowel reduction before versus after a word's uniqueness point. Therefore, there is no evidence that speakers' production reflects sensitivity to word-internal information-load that is known to affect lexical access.

These previous experiments, then, suggest limits to the sensitivity of lexical confusability adjustments to sublexical detail, although neither offered any predictions specifically about whether *segment*-level confusability triggers adjustments of that segment in hard words. The results presented in this chapter fill that gap by indicating that confusability by a particular segment is *not* necessary to induce coarticulatory adjustments of that segment. Lexical effects on speech production, then, are quite general, and accommodations to lexical confusability occur at the word-level rather than sublexically.

Chapter 6: Summary and General Discussion

6.1. Summary of Results

This dissertation has investigated the relation between coarticulation and the lexicon. The main goal was to provide a clear description of the effect of this relation on coarticulation. To this end, four types of coarticulation were chosen for study: anticipatory and carryover nasal coarticulation and anticipatory and carryover vowel-to-vowel coarticulation. A corpus of English words exhibiting the environment for these types of coarticulation was designed, as described in Chapter 2, such that the words fell into one of two categories with respect to their lexical confusability, calculated as relative frequency: low-*R* (hard) or high-*R* (easy).

The main results, for English, were reported in Chapter 3, where the degree of coarticulation in high-*R* and low-*R* words was compared. With respect to all types of coarticulation examined, anticipatory and carryover nasal and vowel-to-vowel, *more* coarticulation was found in low-*R* (hard) words than in high-*R* (easy) words. In the nasal coarticulation test words, vowels in the low-*R* words were more nasalized, as measured by an acoustic correlate of nasality, A1-P0. In the vowel-to-vowel coarticulation test words, both of the vowels in low-*R* words were acoustically further from their theoretical canonical values than vowels in high-*R* words, apparently pulled away from canonical due to the influence of the other vowel in the word. That this deviation was indeed due to coarticulation was additionally supported by the finding that the vowels in low-*R* words were acoustically closer to the opposite vowel than those in high-*R* words, at least for V1s.

In that chapter, lexical effects on vowel reduction or hyperarticulation and their relation to coarticulation were also investigated. Previous findings that vowels are, for the most part, less reduced or more hyperarticulated in hard (low-*R*) words (Wright, 2004) were replicated. It was found that vowels in the low-*R* monosyllabic nasal test words were further from the vowel space center (i.e., hyperarticulated) than the vowels in the high-*R* words. Similar results were found for the vowels in the CVCV words: for the V1s in CVC/i/ and V-matched words and for the V2s in CVC/i/ words, vowels from low-*R* words were more peripheral than those from high-*R* words. These results also reflect Wright's findings in that point vowels (those at the corners of the vowel space) were hyperarticulated in low-*R* words while other vowels (e.g., /o/) were relatively unaffected.

Since both increased coarticulation and hyperarticulation were found in low-*R* words, it was shown that coarticulation is not antithetical to hyperarticulation. However, it was also shown that while increased coarticulation and hyperarticulation co-occur, they are not exactly the same phenomenon. Increased coarticulation was found for vowels in all low-*R* words, while hyperarticulation was found for some vowels in low-*R* words but not for all.

In Chapter 4, these findings were extended to French. The degree of nasal coarticulation in high-*R* and low-*R* French words was compared. With respect to at least carryover nasal coarticulation, *more* coarticulation was found in low-*R* (hard) words (with non-high, nasal-contrastive vowels) than in high-*R* words, as indicated by a greater degree of nasality in the low-*R* words.

Chapter 4 also addressed the role of phonological contrast in mediating the relation between lexical confusability and coarticulation. The effect of the presence of potential contrast was examined at two levels: at the general language level and at the phoneme level. French, unlike English, uses nasality to distinguish vowels phonemically. In fact, however, there are fewer nasal vowels than oral ones, so only a subset of French vowels actually do contrast with another vowel by nasality. Since lexical confusability was found to partially predict the degree of nasal coarticulation in at least some subset of French words, it was shown that the involvement of a particular phonetic parameter in producing phonological contrast in a language does not preclude the involvement of that parameter in lexically-based adjustments of coarticulation. In a sense, this is no different from the case of a vowel-to-vowel effect in a language in which, like all languages, vowels contrast with respect to their vowel quality. And since the subset of words in which the *R* effect was found was the nasal-contrastive set (the set containing vowels which actually have a nasal counterpart), it was shown that not even the existence of a *specific* phonological contrast precludes lexically-motivated adjustments in coarticulation. However, the effect of lexical confusability on coarticulation *was* shown to be sensitive to phonologically *limited* contrasts in a language. Contrary to the initial predictions, no effect of lexical confusability on coarticulation was found in words with non-contrastive vowels or in VNs with nasal-contrastive vowels (where the vowel is in the non-contrastive, pre-nasal position).

In Chapter 5, the focus of the investigation of the sensitivity of the *R* effect to various contrasts was moved back to English and to specific lexical or sublexical contrasts within a neighborhood. Low-*R* and high-*R* anticipatory nasal coarticulation test words were further categorized by whether or not they were confusable by each of the segments primarily involved in the nasal coarticulation: the nasal and the vowel. No difference in the influence of lexical confusability (*R*) on coarticulation was found: low-*R* words showed greater coarticulation than high-*R* words, regardless of the individual contribution of either the nasal or the vowel to the overall confusability of a word.

6.2. General Discussion

6.2.1. Speaker effects vs. listener effects

As stated previously, the main purpose of this study was to provide a clear description of the effect of the structure of the lexicon on coarticulation. In the process, questions have also been posed that address the sensitivity of this effect to other language-internal structural factors that might interact with it. The factors that were chosen are ones that, like relative frequency, seem to have the potential to play a role in word-specific or lexical confusability. These are also factors that, if speakers were benevolently accommodating listener difficulties, might be predicted to be accommodated as well, or might mediate the accommodations being made with respect to *R*. But although a functional account of the effect of lexical factors on coarticulation was considered in Chapter 3, we have remained somewhat agnostic so far about whether the lexical effect on coarticulation is, in fact, listener-directed.

It was not part of the design of the current study to confidently support or deny a teleological claim about the effect, but insofar as the data from Chapters 3, 4 and 5 reflect on such a claim, it can be evaluated here. As was just stated, throughout the dissertation, various confusability-related factors were investigated with the purpose of seeing whether they interact with the lexical effect on coarticulation. And these happen also to be factors that, if they were found to have an effect on *R* (or on coarticulation independently), would strongly suggest a sensitivity of the effect to listener difficulties. (This is not to say that such interactions are *required* of a listener-directed account, but rather that their explanation outside of such an account, while not necessarily impossible, is less straightforward.) But although several attempts were made at finding an influencing factor—direction of coarticulation, existence of phonological contrast, segment-specific confusability—the basic effect of *R* was simply found to be robust and insensitive. No particular evidence was found suggesting a listener-directed effect.

Thus, we will explore for the moment an alternative account. Recall that, as outlined in Chapter 1, there are at least two major possibilities for explaining how an effect of lexical confusability on speech production might come about. There is the account in which speakers adjust their pronunciation in response to their estimation of a listener's difficulty in perceiving and processing their message. On this view, speakers know, at least tacitly, that low relative frequency (and both low frequency and high neighborhood density independently) lead to difficulty in lexical access for the perceiver, so they try to compensate for the increased demand on listeners in those hard words by pronouncing them in such a way that they are easier to perceive. But there is also the account in which the adjustments are related to the demands on the speaker and not to those on the listener. In this account, speakers have their own difficulty in lexical retrieval during speech production, which yields an automatic on-line adjustment in production. This effect is still related to lexical confusability, but the difficulty is on the part of the speaker rather than the listener.

This account is compelling because of its straightforward way of explaining the means by which a speaker has access to information about lexical confusability and, in principle, how that results in speech modifications. However, this apparent straightforwardness is also one of the account's weaknesses. In making the mechanism for the effects automatic and simple, it leaves unexplained why *particular* types of adjustments are made. This gap is not outside the attention of current research (e.g., work by Jurafsky and colleagues), but this research has still not led to a clear answer. But perhaps a more fundamental problem with this account lies in the difference between the data for which it has been most adequately worked out and the data we would like to apply it to in this dissertation. It is lexical *frequency* effects on reduction that have been best described. The data in this dissertation, however, involve effects of *relative frequency*, which comprises both lexical frequency and neighborhood density. And in fact, *R* in this study is much more highly correlated with neighborhood density than with frequency (which is actually balanced across *R* categories). Although the lexical confusability metric has been called "relative frequency", it might better be thought of as a kind of frequency-weighted neighborhood density measure. When the effects of these two lexical factors—frequency and neighborhood density—are considered *together*, we will see that the speaker-oriented account is no longer so straightforward, and we are led again to consider that the effects are in fact listener-oriented.

Let us look first just at frequency effects. From a listener-oriented perspective, we can predict that, since low frequency words are more difficult in lexical access, appropriate listener-directed accommodations would be those that would make low frequency words easier to perceive (for example, hyperarticulation). From a speaker-oriented perspective, we have no a priori predictions about the direct effect of lexical difficulty on production, so we have no reason to believe that the result could not be the same—hyperarticulation in low frequency words. Therefore, these two possible accounts cannot be differentiated by means of the data. When neighborhood density effects are considered along with the frequency effects, however, the predicted patterns of effects are different under the two accounts. The effects of frequency and those of neighborhood density have been shown to be very closely related: *low* frequency words and *high* density words pattern together such that both resist reduction, for instance (as shown in the "effect on hyperarticulation" column in Table 12). In Chapter 1, however, it was discussed that neighborhood density plays a different role in lexical access in speech production, where it is *facilitative*, than it does in speech perception, where it is *inhibitory*. (Compare the "listener" and "speaker" columns in Table 12.) So with respect to the difficulty of lexical access for a talker during speech production, low frequency and high density words do not suggest the same automatic effects since *low* frequency words are hard for speakers while *high* density words are easy. So if difficulty in lexical access is to have a consistent effect, it must be difficulty on the part of the *listener* that is playing the active role, since both low frequency and high neighborhood density render lexical access difficult for listeners and also result in the same effects in production. Note in Table 12 that there is a match between frequency and density effects on hyperarticulation and listener difficulty (there is less reduction when access for the listener is hard) but a mismatch between frequency and density effects and *speaker* difficulty. These facts lead to the conclusion that the effect of *R* found in this dissertation also arises from lexical difficulty in perception rather than in production and thus support a view of this effect as listener-directed.

word type	**listener** (recognition)	speaker (retrieval)	effect on hyperarticulation	effect on coarticulation
low frequency high frequency	**hard** easy	hard easy	**less reduced** more reduced	? ?
low density high density	easy **hard**	hard easy	more reduced **hyperarticulated (less reduced)**	less coartic. **more coarticulation**

Table 12 Effects of frequency and neighborhood density on lexical difficulty for speakers and listeners. Note that words that are hard for listeners in lexical recognition show the same phonetic effects with respect to hyperarticulation, while there is no consistent pattern of effects according to lexical difficulty for the speaker.

Clearly this conclusion hinges on the assumption that the observed role of neighborhood density in production and perception is directly mediated by lexical access. This assumption is of particular relevance with respect to production since there is the potential confounding influence of articulatory ease. Experimental responses in studies designed to look at lexical effects on production (e.g., elicited speech errors, picture-naming) generally involve not only lexical access and decision, but also some sort of articulatory plan and execution. (Compare this with studies on lexical perception, in which responses involve lexical access, decision, and usually a button-push.) For example, in the case of picture naming, the response latency measures the time required to make a decision about the identity of the object, access its lexical representation, make an articulatory plan, and begin its execution. The facilitation seen for high neighborhood density in production could plausibly occur, then, *after* lexical access during the articulatory planning phase. In this scenario, high density words might be as difficult to access from the lexicon for speakers as they are for listeners[6]. The advantage for high density words, then, would come in the articulatory planning. The various chunks of high density words occur in a large number of neighbors and so are well-practiced, leading to facilitation of articulatory planning and execution for these words relative to low density words. (This effect would seem to rely on neighborhood frequency as well.) Under this story, the influence of articulatory ease out-weighs the difficulty of lexical access to yield a net gain in efficiency in production for words with a high neighborhood density.

This type of study bears comparison, then, to word-naming (i.e., word repetition) tasks. Such tasks investigate the timing of lexical access in auditory word recognition, but like the picture-naming tasks, they require both lexical access and articulatory implementation. As in other sorts of lexical perception tasks, words with more neighbors are named more slowly than words with fewer neighbors (Luce and Pisoni, 1998; Vitevitch and Luce, 1998). These results indicate that, contrary to the assumption

[6] It is not obvious that lexical retrieval requires activation of phonological entries and thus the set of phonologically related neighbors, although the relatively common occurrence of malapropisms (e.g., saying *button* instead of *butter*) (Fromkin, 1971) suggests that such activation does occur.

necessary for the story just above, the inhibitory effect of density on lexical access outweighs any advantage in articulatory planning that high density words may have. And they suggest that, contrary to the story just above, the facilitation of speech production by high neighborhood density is in fact due to lexical access (as claimed by Vitevitch (2002) and Dell and Gordon (2003)).

An explanation for the confluence of the effects of low frequency and high neighborhood density on various phonetic phenomena, then, must be able to account for (or allow for) the confluence of the effects of low frequency and *low* neighborhood density on the ease of lexical retrieval in speech production. This limits the plausibility of an explanation in which the difficulty of lexical retrieval for speakers (due to both frequency and neighborhood density) yields the correct automatic effects on phonetic implementation. And these facts lead us back, then, to a functional listener-oriented account of the lexical confusability effect on coarticulation, despite the lack of sensitivity of the effect to other confusability factors.

6.2.2. Implications for Phonetic Implementation

What does it mean that the effect of *R* on coarticulation is not sensitive to other confusability factors? In fact, from a functional point of view, it means that talkers accommodate more than necessary. In the case of direction of coarticulation, for example, it means that they provide following cues as well as preceding ones. (Even if both types of cues can be used, preceding cues still precede, so in terms of promoting efficiency in lexical recognition, they are still arguably more useful.) In the case of the lack of segment-specific confusability accommodations, it means that speakers make everything clearer in less clear words, providing even more redundant information. These facts make the effect robust not only in its occurrence, but also in its potential usefulness to listeners.

Aside from trying to be maximally helpful, one could also imagine that speakers make very general speech adjustments in order to simplify the computation necessary to keep track of the context for all of these accommodations. And even outside of a listener-directed account, the fact that the *R* effect is insensitive to other structural confusability factors suggests that the coarticulatory modifications are directly related to factors in the structure of the lexicon—frequency and neighborhood density—and not to some more abstract, and more complicated, notion of confusability (albeit one that might take lexical factors into account).

We should briefly consider how speakers might keep track of lexical confusability. One seemingly simple option would be for them to rely on their own difficulty in lexical access, but as we established in the preceding section, this cannot be the case since listener difficulty and speaker difficulty in lexical access do not fully coincide, and it is listener difficulty with which the accommodations pattern. The absence of the possibility of getting lexical confusability information from the process of lexical retrieval suggests that the information is instead represented in memory. Of course, speakers are also listeners, so they might simply be extremely good at monitoring the communicative situation and projecting from their experience as listeners as to how various factors (including lexical factors) would affect the success of communication (just as they might if they were speaking in noise). But such projection from word to word without reference to some stored facts seems extremely cumbersome. Whereas adjustments in stylistic register are across-the-board, such that once a speaker determines that an adjustment will be made, all words throughout an utterance undergo it, adjustments related to lexical factors must be figured out word-by-word.

How, then, might lexical confusability be represented? One possibility is that speakers could actually calculate lexical confusability online from information stored in the representations of target words and neighbors—perhaps quantitatively (as in calculating *R*), or perhaps in some more abstract manner. Alternately, and much more efficiently, speakers might instead simply refer to some designation of a word's lexical confusability (something like *R*, or even a simple binary tag indicating *high-R* or *low-R*) that was stored as part of the long-term representation. (The data in the current study show only a categorical difference between high- and low-*R* words with respect to the degree of coarticulation, so there is no evidence at this point that coarticulatory adjustments are sensitive to the gradience of *R*.) But in either case, speakers get necessary information about lexical confusability by referring directly to information stored in lexical representations.

6.2.3. Implications for a View of Coarticulation and Hyperarticulation

Finally we return to a discussion of the implications of the functional account explored in this dissertation for a view of coarticulation. As was discussed in Chapter 3, a functional interpretation of the data requires that coarticulation be beneficial to listeners.

Not only does this conflict with certain theories of coarticulation (e.g., Lindblom), but it also appears to conflict with some previous clear speech data. Both Duez (1992) and Krull (1989), for instance, find less C to V contextual influence in citation speech, which has been interpreted as more careful, clear speech, than in spontaneous speech. But the current data are not quite so inconsistent with other clear speech data, such as recent studies by Bradlow (2000) and Matthies, et al. (2001) that found no difference in degree of coarticulation between clear and normal speech. And I will argue that they are not actually inconsistent with the Krull and Duez data either.

Many of the differences between previous studies (and between these studies and the current data) may lie in the interpretation of the experimental conditions or what constitutes "clear speech". In the case of both the Krull and Duez studies, the speech styles compared were experimentally-elicited citation speech and spontaneous speech. And although citation speech may in some sense be more careful than connected spontaneous speech, it has no explicit communicative function—it is not listener-directed. Spontaneous speech, on the other hand, is speech produced in a natural communicative situation in which a speaker is actually seeking to be understood by a listener. Therefore, the Krull and Duez data are not inconsistent with the findings in the current study: more coarticulation is found in those situations in which speakers are trying hardest to be understood. In the case of the Bradlow and Matthies, et al. studies, the clear speech is elicited by asking subjects to "speak clearly" or to "speak as if to a listener with hearing loss or from a different language background" (Bradlow, 2000), leading to a speech style that may not quite accurately represent the natural clear speech that speakers would use in a genuine communicative situation. This slight unnaturalness may limit somewhat the coarticulatory adjustments that would be seen in actual listener-directed speech.

Even so, Bradlow (2002) argues that coarticulation is a natural property of clear speech. She explains her effect by saying, "the force towards enhanced acoustic distinctiveness in clear speech production applies equally to all segments thereby actually *causing* the apparent maintenance of coarticulation. In the case of a CV syllable, both the consonant and the vowel would be subject to hyperarticulation in clear speech, resulting in more extreme articulatory targets for both the C and the V… Thus, under this explanation, the maintenance of coarticulation is a direct consequence of the "global" hyperarticulation that characterizes clear speech" (p. 267-8). In other words, Bradlow assumes a sort of balanced hybrid of the two scenarios hypothesized for hard words in Figure 2. Recall that in one scenario, gestures became more distinct by narrowing temporally in order to reduce the amount of overlap (i.e., coarticulation). In the other scenario, gestures became larger, leading to more overlap. In Bradlow's data, however, there is neither an increase nor a decrease in the overall amount of coarticulation in clear speech relative to normal speech. Her story, then, is that the requirements of clear speech drive gestures to become more distinct both by pulling in the gestures to reduce overlap and by increasing the size of gestures by aiming for more extreme targets. With respect to the degree of coarticulation, these two adjustments cancel one another out, as illustrated in Figure 33.

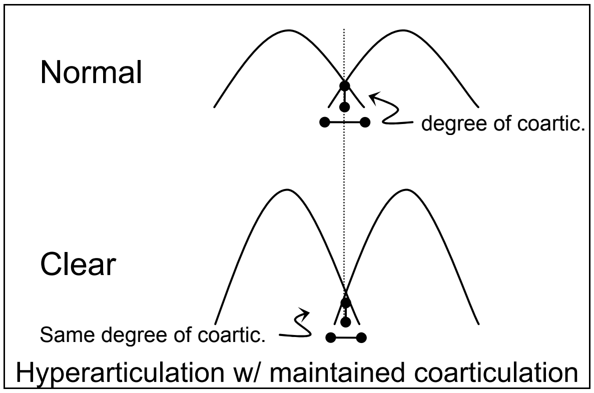

Figure 33 A schematization of Bradlow's view of the relation between hyperarticulation and coarticulation in clear speech. The figure shows hyperarticulation involving both a more extreme target and a more temporally distinct gesture, yielding the same net degree of coarticulation in normal and clear speech.

But the data presented in this dissertation indicate that Bradlow's view of the relation between hyperarticulation and coarticulation is too constrained, at least for lexically-mediated adjustments. As Wright (2004) showed, and as was confirmed in the data in this study, there *is* hyperarticulation in "hard" words (consistent also with Bradlow's assertion that there is more hyperarticulation in "clear speech"). But my data show *coarticulation* to be pervasive in hard words as well—even more pervasive than hyperarticulation (and more pervasive than in easy words). This suggests, then, that both Wright and Bradlow may be slightly wrong about the direct motivation for the hyperarticulation. Coarticulation is not a mere byproduct of hyperarticulation. Rather, it is a distinct phenomenon that colludes with hyperarticulation in the adjusted production of lexically confusable words. The goal of the hyperarticulation, then, must not be to increase the distinctiveness of vowels by making them more distant from one another. Rather, the goal is to make the cues to the segments in individual words as strong as possible. After all, it is distinctions among words (which are segments *in their context*) and not among individual isolated vowels that must ultimately be well-maintained and expressed in language. And *in* context, coarticulatory cues can be parsed efficiently by listeners. Hyperarticulation and coarticulation, then, are two ways of accomplishing the same thing: expanding cues. Thus the hyperarticulation found in low-*R* (or hard) words, understood in this way as the expanding of cues, not only may lead to coarticulation, but it is also actually achieved to some degree *through* coarticulation.

6.3. Directions for Continuation

This study, in presenting a new body of data showing the influences of the structure of the lexicon on coarticulation, has also inevitably left the interpretation of certain details unresolved and has raised a whole new set of questions, particularly about the interaction of this coarticulation effect with other phonetic and communicative effects. For instance, although an effect of *R* was found in both the stressed and the unstressed syllables examined, the interaction between stress and lexically-mediated adjustments in coarticulation could not be fully explored in the current design due to the confound between stress and direction of coarticulation in the CVCV words. Therefore, the differences that did emerge between the effects seen on V1 and those seen on V2 could not be unqualifiedly attributed to the difference in stress. And since the role of stress could not be isolated, a complete explanation of how stress might lead to these differences could not be developed. Further investigation of the effect of stress on lexically-mediated coarticulation would be interesting, then, as it would bear on the nature of the effects of lexical factors on speech production and on the relation between stress and coarticulation more generally. And it would also be of significance insofar as understanding this relation could help to sort out some of the unresolved details of the carryover V-to-V results.

Certain unanticipated findings from the dissertation also suggest interesting bases for further research. One such finding concerns the effect of phonological contrast on the lexically-based adjustment of coarticulation. It was shown by means of the French data that the existence of a phonological contrast in a language does not limit the ability of the phonetic property involved in that contrast to play a role in the increased coarticulation found in lexically confusable words. But the effect of *R* on coarticulation *was* limited in certain contrastiveness contexts—namely, those contexts in which a possible phonological contrast was actually prohibited: in non-contrastive (high) vowels and pre-nasally. This finding is interesting because it is in some sense contrary to the intuition expressed in the hypotheses of Manuel (1990) and Manuel & Krakow (1984) and Flemming (1995) and others. But it seems not to be the presence or absence of contrast itself that actually conditions the effect. Rather, the aspects of the phonological grammar that influence the limits on contrast also limit the *R*-related adjustments. Further study of the relation between the effect of *R* on coarticulation and phonological contrast (perhaps with respect to other types of coarticulatory cues and other types of contrast) could help to show what sort of interaction the effect has with the phonological grammar. And it would also contribute in an interesting way to the discussion of the role of contrast in constraining coarticulation, in particular, and in influencing phonological and phonetic processes, in general.

Another especially interesting finding in this dissertation was that hyperarticulation and coarticulation work at least partly independently as adjustments made in lexically confusable words. The functional relation between these two phenomena has been discussed above. But the physical relation between them bears further systematic investigation. Establishing the articulatory means by which the two phenomena are realized would help to better our understanding of the coarticulatory adjustment and also our interpretation of how the two effects influence one another.

The current study also suggests future exploration of the interaction between the *R* effect and external confusability factors. In this dissertation, several factors were examined that might play a role in confusability and interact with the straightforward lexical factors that constitute *R*. These were structural factors like direction of coarticulation (or position of the coarticulatory cue relative to the source segment), the role of the cue provided by coarticulation in phonological contrast, and the role of individual segments in specific potential confusions. However, the question remains as to whether external factors can also influence the confusability of a word and, in turn, its coarticulatory realization. There are word-specific or utterance-specific factors that might influence the confusability of individual words (e.g., predictability in context, repetition) as well as factors specific to the larger communicative context (e.g., noise, listener's native language or hearing condition) that influence the confusability not just of specific words, but of all words generally. Understanding what factors contribute to the measure of lexical confusability according to which speakers adjust their production of coarticulation is critical to understanding how to model the phonetic implementation of the production of coarticulation. And the interpretation of lexical effects as listener-oriented would gain further support if those same accommodations were found in more straightforwardly listener-directed speech.

6.4. Concluding Remarks

The data in this dissertation significantly bear on and link two areas of study: coarticulation and the role of the structure of the lexicon. They show that degree of coarticulation is a word-specific phonetic detail conditioned by lexical factors. Specifically, there is a greater degree of coarticulation in more lexically confusable words (those with a low relative frequency). This effect was found across types of coarticulation (nasal and vowel-to-vowel), across directions of coarticulation (anticipatory and carryover), across stress conditions (in both stressed and unstressed syllables for vowel-to-vowel coarticulation), and across languages (in both English and French). And the data do not reveal that the effect on coarticulation is constrained by either phonological or specific lexical contrasts. All in all, then, the effect of lexical confusability (R) on coarticulation has been shown to be both robust and general. Further, it has been argued that the effect can be given a successful functional, or listener-directed, account. And in providing a description of the relation between coarticulation and the lexicon and the effect of this relation on the production of coarticulation, the dissertation has also framed the task of understanding the mechanisms by which lexical factors shape the realization of coarticulation, in particular, and phonetic implementation, in general.

Appendix 1. All English Nasal Test Words with Log Frequency, Neighborhood Density, and Relative Frequency (*R*)

	word	log freq	# of neigh	*R*
Low-*R* CVNs	bum	1.9494	27	0.0277
	thyme	1.7324	25	0.0301
	fame	2.2430	24	0.0356
	yam	1.1461	18	0.0370
	vend	1.2304	12	0.0439
	gong	1.5563	13	0.0512
	prom	1.2553	10	0.0551
	punt	1.6990	13	0.0578
	shame	2.6618	18	0.0581
	bang	2.7110	18	0.0602
	dawn	2.8401	21	0.0607
	band	2.9299	17	0.0617
	thumb	2.7168	15	0.0660
	groan	2.4166	14	0.0661
	found	2.7356	15	0.0669
	home	3.9841	23	0.0684
	lawn	2.6830	17	0.0687
	bran	1.6532	11	0.0701
	rank	2.7987	20	0.0730
	tend	3.3685	17	0.0746
	tongue	2.8543	17	0.0772
	drawn	1.6721	8	0.0842
	dump	2.6075	14	0.0852
	bland	2.0170	8	0.0872
	MEAN	2.3109	16.5	0.0611

	word	log freq	# of neigh	*R*
High-*R* CVNs	stone	3.3444	11	0.1246
	stomp	1.6532	4	0.1287
	strain	2.9965	8	0.1296
	chomp	1.3802	6	0.1311
	frame	2.9138	7	0.1334
	swan	2.1523	9	0.1462
	plump	2.4456	7	0.1487
	sprain	1.5051	3	0.1531
	flunk	1.2304	5	0.1561
	ground	3.5103	6	0.1689
	plank	2.1004	6	0.1744
	trench	2.2601	4	0.1794
	romp	1.6021	4	0.1938
	blonde	2.6484	4	0.2096
	tempt	2.5250	4	0.2099
	stem	2.7388	5	0.2108
	trunk	2.6618	3	0.2728
	dance	3.2639	4	0.2761
	strand	2.4249	3	0.2803
	swamp	2.3181	4	0.2874
	front	3.6729	5	0.2967
	scant	1.6232	2	0.3006
	glance	3.1694	3	0.3059
	crunch	2.0682	3	0.3277
	MEAN	2.4254	5.0	0.2061

Continued on the next page

	word	log freq	# of neigh	*R*
Low-*R* NVCs	moat	1.6232	28	0.0257
	mate	2.7324	39	0.0279
	nab	1.0000	18	0.0337
	mast	1.7782	16	0.0377
	muff	1.4150	17	0.0382
	might	3.7466	34	0.0399
	night	3.9195	35	0.0410
	nap	2.0755	23	0.0437
	mile	3.4878	31	0.0446
	note	3.4976	30	0.0463
	mike	2.7513	23	0.0478
	mess	2.7760	21	0.0498
	mug	2.2355	22	0.0525
	knock	3.0406	27	0.0552
	nest	2.5366	17	0.0570
	mouse	2.5185	18	0.0605
	notch	1.7160	12	0.0652
	moth	1.9823	14	0.0690
	nose	3.1706	15	0.0731
	neck	3.1658	17	0.0832
	MEAN	2.5585	22.9	0.0496
	GRAND MEAN	2.4234	19.4	0.0559

	word	log freq	# of neigh	*R*
High-*R* NVCs	snob	1.6721	8	0.1262
	mild	2.6998	7	0.1286
	snap	2.7694	10	0.1311
	melt	2.6395	10	0.1312
	smell	3.2408	7	0.1317
	smut	1.2041	6	0.1331
	snake	2.6571	8	0.1491
	mouth	3.4223	8	0.1550
	snipe	1.5185	5	0.1635
	mesh	1.9912	4	0.1713
	smile	3.6415	6	0.1760
	small	4.0321	9	0.1827
	snout	1.6990	4	0.1899
	smash	2.6955	6	0.2008
	smoke	3.2196	6	0.2221
	smog	1.5315	3	0.2457
	smudge	1.8062	4	0.2532
	noise	3.1418	4	0.2618
	snatch	2.5539	3	0.2757
	next	3.9123	2	0.4213
	MEAN	2.6024	6.0	0.1925
	GRAND MEAN	2.5058	5.5	0.1999

Appendix 2. All English CVCV Test Words with Log Frequency, Neighborhood Density, and Relative Frequency (*R*)

	word	log freq	# of neigh	*R*
Low-*R* CVC/i/s	sappy	0.6021	11	0.0357
	tacky	1.2553	13	0.0561
	pushy	1.0000	7	0.0831
	bootie	1.3802	12	0.0605
	bookie	1.1761	9	0.0762
	buddy	2.0531	17	0.0703
	muddy	2.2856	14	0.0732
	muggy	1.0000	8	0.0629
	petty	2.3766	20	0.0633
	mosey	0.6990	6	0.0673
	poppy	1.7993	14	0.0862
	knobby	0.9542	9	0.0639
	MEAN	1.3818	11.7	0.0666
Low-*R* CVC/o/s	lotto	0.3010	3	0.0350
	gecko	0.4771	2	0.0850
	mellow	1.8573	10	0.0880
	willow*	2.0645	10	0.0894
	marrow	1.8261	9	0.0970
	shallow	2.4871	12	0.1099
	MEAN	1.5022	7.7	0.0841
Low-*R* perf set	seaway	0.0000	3	0.0000
	speedo	0.0000	2	0.0000
	willow*	2.0645	10	0.0894
	nosy	1.5315	7	0.1004
	phoney	2.0170	9	0.1024
	lacy	1.6335	6	0.1069
	MEAN	1.2077	6.2	0.0665
	GRAND MEAN	1.3381	9.3	0.0701

	word	log freq	# of neigh	*R*
High-*R* CVC/i/s	shabby	2.1875	4	0.2629
	shaggy	1.8573	5	0.2337
	floozy	0.6021	0	1.0000
	fruity	1.3979	2	0.2184
	spooky	1.3802	2	0.3083
	chubby	1.5798	4	0.2546
	fussy	1.8451	6	0.1858
	guppy	1.9542	5	0.2306
	dressy	0.8451	2	0.1953
	grouchy	0.6021	1	0.5000
	floppy	1.6021	2	0.2877
	groggy	1.2553	2	0.5000
	MEAN	1.4257	2.9	0.3481
High-*R* CVC/o/s	ditto*	1.30103	3	0.21734
	pillow	2.54407	4	0.23132
	kilo*	1.79934	2	0.37954
	swallow	2.81425	1	0.61378
	sparrow	1.89763	0	1.00000
	stucco	1.77815	0	1.00000
	MEAN	2.0224	1.7	0.5737
High-*R* perf set	ditto*	1.3010	3	0.2173
	throaty	1.2041	1	0.2907
	stony	2.0792	2	0.2955
	flaky	1.1461	1	0.3346
	kilo*	1.7993	2	0.3795
	leeway	0.8451	2	0.3863
	MEAN	1.3958	1.8	0.3173
	GRAND MEAN	1.5690	2.3	0.4058

* Word is in both CVC/o/ and perfect sets.

Appendix 3. All English Canonical Vowel Words with Log Frequency, Neighborhood Density, and Relative Frequency (*R*)

	word	log freq	# of neigh	*R*
æ	gab	0.3010	22	0.0076
	tack	1.9638	48	0.0253
	cache	1.4314	27	0.0273
	ad	2.2304	28	0.0296
	hack	2.1523	39	0.0299
	sap	1.8513	29	0.0308
	pat	2.5441	42	0.0316
	hash	1.6532	21	0.0325
ɑ	saw	1.9445	37	0.0244
	watt	2.0828	40	0.0266
	cob	1.5798	28	0.0279
	wad	1.8325	40	0.0282
	paw	2.1303	35	0.0319
	dot	2.4518	29	0.0326
	cod	2.2480	36	0.0339
	cop	2.4857	39	0.0385
aʊ	pout	1.8388	23	0.0337
	cow	2.8751	29	0.0482
	how	4.3261	34	0.0598
	shout	3.2368	17	0.0727
	doubt	3.5269	19	0.0786
	pouch	1.9590	12	0.0820
	out	4.6564	21	0.0876
	house	4.0457	16	0.0878
ɛ	wed	1.1461	33	0.0142
	etch	1.7243	28	0.0236
	pet	2.5740	35	0.0309
	bet	2.7582	39	0.0322
	peck	2.0645	31	0.0323
	wet	3.0828	38	0.0348
	debt	2.7679	29	0.0359
	vet	2.1987	22	0.0391
eɪ	ace	1.9085	34	0.0227
	wade	2.1732	38	0.0275
	ache	2.4829	33	0.0281
	hay	2.4249	51	0.0284
	fake	2.3160	29	0.0310
	ape	2.3385	25	0.0335
	fate	2.7889	42	0.0342
	bake	2.6263	39	0.0343

	word	log freq	# of neigh	*R*
i	pea	2.2455	69	0.0228
	beak	2.0792	41	0.0252
	peach	2.0170	37	0.0284
	fee	2.7582	61	0.0286
	bead	2.3502	48	0.0299
	deed	2.2553	28	0.0299
	seize	2.7627	32	0.0304
	tea	3.2114	66	0.0305
oʊ	oat	1.6532	29	0.0212
	tote	1.6232	32	0.0251
	dough	2.2648	49	0.0268
	sew	2.3032	56	0.0281
	owe	2.6866	57	0.0283
	coke	2.0453	35	0.0288
	hose	1.9294	21	0.0301
	toe	2.7243	56	0.0348
u	toot	1.3424	30	0.0197
	boo	1.5798	55	0.0221
	hoot	1.9294	35	0.0244
	sue	2.3424	45	0.0286
	zoo	2.2380	30	0.0296
	hoop	1.7782	25	0.0331
	booze	1.8921	22	0.0391
	boot	2.8506	38	0.0425
ʌ	puck	0.9031	33	0.0133
	hutch	0.8451	17	0.0202
	pup	1.3010	23	0.0276
	dud	1.1761	20	0.0290
	sub	1.5682	21	0.0307
	bud	2.1732	31	0.0310
	buck	2.3598	38	0.0321
	buff	1.6721	24	0.0335
	MEAN	2.2164	34.2	0.0333

Appendix 4. All French Nasal Test Words with Log Frequency, Neighborhood Density, and Relative Frequency (*R*)

	word	log freq	# of neigh	*R*
Low-*R* VNs – non-contrastive V	devine	2.6365	92	0.0166
	saline	1.3979	27	0.0493
	allume	2.5988	27	0.0547
	bambine	0.6021	9	0.0556
	abîme	2.6128	34	0.0591
	marine	3.1048	40	0.0619
	patine	1.8633	33	0.0628
	indigne	2.3263	22	0.0633
	babines	1.6721	24	0.0645
	insigne	2.0294	16	0.0651
	lapine	0.9031	15	0.0654
	épine	2.0294	25	0.0685
	coquine	1.3010	12	0.0710
	centimes	2.1173	15	0.0717
	cabine	2.7050	19	0.0807
	bassine	2.0294	22	0.0836
	MEAN	1.9956	27.0	0.0621

	word	log freq	# of neigh	*R*
High-*R* VNs – non-contrastive V	narine	1.9294	6	0.1549
	cantine	2.2788	13	0.1672
	terrine	1.8388	11	0.2174
	intime	2.8954	11	0.2337
	dauphine	2.1931	7	0.2596
	routine	2.3927	5	0.2987
	sardines	2.2227	7	0.3239
	praline	0.9031	4	0.3672
	agrumes	1.3424	2	0.3785
	ballerine	1.3424	2	0.5394
	cousine	2.6085	8	0.5909
	vaseline	1.3979	2	0.6667
	vitrine	2.5490	2	0.7026
	morphine	1.4771	1	0.8307
	ultime	2.7059	1	0.8501
	piscine	2.4082	1	1.0000
	MEAN	2.0304	5.2	0.4738

Low-*R* VNs – nasal-contrastive V	bedaine	1.4472	122	0.0077
	cône	2.0828	103	0.0114
	panne	2.3874	92	0.0169
	gomme	2.3243	85	0.0187
	arène	2.0000	66	0.0208
	atone	1.2788	29	0.0351
	icone	0.3010	5	0.0383
	haleine	2.6435	48	0.0385
	crème	2.7372	33	0.0582
	douane	2.3201	21	0.0606
	baleine	1.8865	26	0.0619
	entame	1.7324	25	0.0634
	antenne	2.1584	26	0.0652
	psaume	1.6532	14	0.0664
	marraine	2.1584	26	0.0682
	crâne	3.0204	39	0.0713
	MEAN	2.0082	47.5	0.0439

High-*R* VNs – nasal-contrastive V	siam	1.7243	7	0.1800
	ébène	2.0934	9	0.1983
	baptême	2.3502	6	0.2015
	trombone	1.1139	7	0.2045
	lionne	1.6128	4	0.2227
	païenne	1.6532	6	0.2385
	sésame	1.4771	4	0.2395
	douzaine	2.6085	2	0.3214
	obscène	2.1367	4	0.3232
	cyclone	1.8692	4	0.3342
	diplôme	2.8280	4	0.3571
	vilaine	2.2014	4	0.4115
	tisane	1.7853	5	0.4334
	royaume	2.9609	1	0.6055
	sultane	1.7782	2	0.7884
	vingtaine	2.5763	1	0.8438
	MEAN	2.0481	4.4	0.3690

GRAND MEAN	2.0019	37.3	0.0530

GRAND MEAN	2.0390	4.8	0.4230

Continued on the next page

Low-R NVs – non-contrastive V

word	log freq	# of neigh	R
genou	2.6561	117	0.0100
chemise	3.0792	111	0.0173
fenouil	1.2788	42	0.0202
Venise	2.9841	107	0.0240
mini	1.8692	43	0.0259
chenille	1.7634	45	0.0259
tamis	1.8692	29	0.0446
cornu	1.5441	20	0.0484
béni	2.0043	33	0.0503
grenu	1.2041	12	0.0533
minou	1.6532	23	0.0553
amibe	1.0792	10	0.0619
connu	3.4437	34	0.0666
dormi	2.6294	21	0.0677
génie	3.1741	32	0.0681
conique	1.9138	20	0.0686
MEAN	2.1341	43.7	0.0442

High-R NVs – non-contrastive V

word	log freq	# of neigh	R
fémur	1.3010	6	0.1663
humour	2.5717	5	0.1752
sénile	1.7076	8	0.1778
chimie	2.8727	7	0.1854
grenouille	2.2695	6	0.2140
caniche	1.7924	6	0.2297
hormis	2.1584	6	0.2466
sinus	1.6721	5	0.2632
vanille	1.8451	8	0.2767
péniche	2.0043	4	0.3365
garni	2.2201	4	0.4030
clinique	2.7466	2	0.5073
Vénus	2.6493	4	0.5268
humide	2.8686	6	0.5317
nounours	1.5441	0	1.0000
rythmique	1.7482	3	1.0000
MEAN	2.1232	5.0	0.3900

Low-R NVs – nasal-contrastive V

word	log freq	# of neigh	R
menottes	2.0755	115	0.0118
sauna	1.0000	52	0.0150
sonnet	1.5798	64	0.0167
menace	2.9499	101	0.0209
sonar	0.9031	22	0.0311
amer	2.4065	44	0.0340
bonnet	2.5276	56	0.0355
coma	2.1461	41	0.0410
cornet	2.0569	38	0.0410
anneau	2.4969	39	0.0421
format	2.2672	26	0.0457
comète	1.6812	28	0.0559
rameau	2.3747	38	0.0579
tonneau	2.1038	28	0.0587
sommaire	2.3892	22	0.0695
sonnette	2.4014	25	0.0720
MEAN	2.0850	46.2	0.0405

High-R NVs – nasal-contrastive V

word	log freq	# of neigh	R
sénat	2.4014	15	0.1614
tonnerre	2.6010	11	0.1629
tomate	2.0374	7	0.1647
chômage	2.4281	7	0.1647
planète	2.7589	12	0.1787
lunaire	2.1399	9	0.1985
créneau	1.7482	6	0.2310
pruneau	1.3617	3	0.2587
guillemets	1.6232	2	0.4185
homard	1.8195	2	0.4667
fromage	2.5888	4	0.5900
thermos	1.5798	1	0.6700
grammaire	2.3365	5	0.7502
jumelles	2.4456	1	0.7777
hypnose	1.9138	0	1.0000
prunelle	1.7709	0	1.0000
MEAN	2.0972	5.3	0.4496

GRAND MEAN	2.1096	44.9	0.0424

GRAND MEAN	2.1102	5.2	0.4198

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