THE ROLES OF VOWEL HARMONY AND STRESS IN PREDICTING VOWEL-TO-VOWEL COARTICULATION

by

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To my parents, who always believed in me

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ABSTRACT

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Similar phonetic and phonological processes often exist in predictable synchronic relationships across languages: when a process is phonologized, its phonetic predecessor is suppressed or limited in scope to resolve conflicting demands on the relevant set of acoustic cues (Cohn, 1990; Francis, Ciocca, Wong, & Chan, 2006). In the case of vowel harmony and vowel-to-vowel (VV) coarticulation, the diachronic origins of harmony in VV coarticulation are well-supported (Ohala, 1994b), but their synchronic relationship is not fully understood. Studies investigating VV coarticulation in harmonizing languages have found disparate patterns across languages. Beddor & Yavuz (1995) found that in Turkish, which has left-to-right vowel harmony, VV coarticulation is predominantly right-to-left, the opposite of the direction of harmony, while Dye (2015) investigated the harmonizing languages of Wolof and Pulaar and found that VV coarticulation was stronger in each language in the direction paralleling the native harmony process.

A second factor known to influence magnitude of coarticulation in each direction is the location of stress; in general, stressed vowels coarticulate less, leading to the expectation that languages with word-final stress will prefer anticipatory coarticulation, while those with word-initial stress will exhibit greater carryover coarticulation. This dissertation investigates coarticulatory directionality in two harmonizing languages with differing stress profiles, Tatar and Hungarian, and one non-harmonizing language with variable stress, Spanish, in order to better understand how stress and vowel harmony impact language-specific directional preferences in VV coarticulation. The data presented here on stress and coarticulation is the first of its kind in languages with backness harmony.

In the Spanish study, the strongest coarticulation occurred in unstressed vowels, while stressed vowels inhibited coarticulatory magnitude, confirming the results of previous studies

that found reduced coarticulation in stressed vowels (Beddor, Harnsberger, & Lindemann, 2002; Fowler, 1981; Recasens, 2015). Consequently, Tatar is expected to exhibit stronger anticipatory coarticulation due to its word-final stress, and Hungarian is expected to demonstrate stronger carryover coarticulation to accompany its word-initial stress, unless the direction of vowel harmony has an interfering influence on coarticulatory directional preferences.

In the Tatar study, the dominant direction of coarticulation was anticipatory, and some evidence was found that Tatar harmony may be undergoing reanalysis, at least with regard to the marginalized lexical subset of orthographically disharmonic items. The finding of primarily anticipatory coarticulation suggests that (1) stress impacts coarticulatory direction as predicted in Tatar and (2) if the direction of vowel harmony has any impact on coarticulatory direction, it is to suppress coarticulation in the direction parallel to harmony. A more likely scenario is that the directions of harmony and coarticulation are synchronically divorced – that upon phonologization, their fates within the language become separated, as suggested by Beddor & Yavuz (1995).

With regard to Hungarian, the results were mixed. The two target vowels exhibited stronger effects in opposite directions, and both carryover and anticipatory coarticulation were widely present, though anticipatory coarticulation appeared in a broader range of consonant and vowel conditions. The carryover coarticulation found in Hungarian is ascribed to the expected impact of word-initial stress, while other influences must have supported the operation of anticipatory coarticulation.

The results of the three studies are situated within Hyman's (2013; 1976) life-cycle model of phonologization, which recognizes that phonological processes arise from phonetic origins and are eventually lost, returning to the phonetic realm where they originated. With regard to vowel harmony and VV coarticulation, Hyman's model allows for the existence of differing synchronic relationships between the two processes across languages. As vowel harmony progresses through the various stages of phonologization, greater variation across languages in the relationship between harmony and VV coarticulation becomes possible. Furthermore, the complexity of the coarticulatory results explored in this dissertation underscores the wide variety of factors influencing VV coarticulation and undermines global cross-linguistic predictions regarding VV coarticulatory direction.

1. INTRODUCTION

This dissertation investigates the synchronic relationship between vowel harmony and vowel-to-vowel (VV) coarticulation[1] with a particular focus on how the impact of stress on coarticulation mediates its relationship to harmony. Harmony and coarticulation share key traits, acoustic cues, and diachronic origins, but it remains unclear whether they exert a synchronic impact on one another in any way. I will examine coarticulation in two languages with vowel harmony, Tatar and Hungarian, and one without – Spanish – in order to determine whether the presence and direction of vowel harmony in a language play a role in shaping VV coarticulation. These languages were selected to allow for investigation of a potential mitigating factor, word-level stress, which has been shown to impact coarticulatory direction and magnitude in non-harmonizing languages (Beddor et al., 2002; Fowler, 1981; Recasens, 2015). In this introduction, I will provide crucial background on harmony and coarticulation, summarize previous work on synchronic and diachronic relations between these two processes, and introduce the hypotheses and structure of the dissertation.

1.1. The relationship between vowel harmony and VV coarticulation

Vowel harmony and vowel-to-vowel coarticulation, both long-distance processes of vowel-to-vowel assimilation, share many key traits but differ in the domain in which they operate. Vowel-to-vowel coarticulation is gradient and phonetic, while vowel harmony is categorical and phonological. (On occasion, gradience has also been observed in processes demonstrated to reside in the phonology, as in the emerging height harmony of French (see, e.g., Nguyen & Fagyal, 2008). Coarticulation is attested in many typologically diverse tongues, including English, Swedish, and Russian (Öhman, 1966), Turkish (Beddor & Yavuz, 1995), Greek (Nicolaidis, 1999), Italian (Farnetani, 1990), Ndebele, Shona, and Sotho (Manuel, 1990), and Swahili (Manuel & Krakow, 1984), and it is predicted for all languages (Lindblom &

[1] For the sake of brevity, throughout this dissertation, I will use the term "coarticulation" to refer specifically to VV coarticulation; when consonant-to-vowel coarticulation is mentioned, I will specify it clearly with the label "CV coarticulation." In similar fashion, the bare term "harmony" is always used to refer to vowel harmony, never consonant harmony.

MacNeilage, 2011). In coarticulation, assimilation is not complete; instead, a partial or gradient effect occurs, wherein neighboring vowels approach one another in one or more acoustic dimensions. A more limited subset of languages, which I will refer to as "harmonizing languages," exhibits categorical assimilation between vowels – vowel harmony – with regard to one or more features. In vowel harmony, vowels in the affected domain, typically a phonological word, undergo a complete transformation with regard to a particular affected feature, so that they all share a specification for that feature. In Tatar, for example, the plural suffix [-lAr] possesses both front and back allomorphs: the front allomorph surfaces in words with front vowels, such as [kerfeklær] 'eyelashes,' and the back allomorph in words with back vowels, such as [ɒlmɑlɑr] 'apples.' Thus, both harmony and coarticulation involve long-distance assimilation between vowels in differing syllables, whose acoustics and articulation undergo alteration in order to more closely approach a neighboring vowel; in coarticulation, the assimilation is partial, while in vowel harmony, it is complete. While complete harmonization precludes coarticulation along the affected dimension, harmony and coarticulation can coexist in a language in one of two ways. The first of these is dimensional separation: harmony in one dimension, such as backness, does not interfere substantially with coarticulation in other dimensions, such as roundness and height. The second is lexical separation, wherein a subset of the lexicon fails to harmonize, giving coarticulatory processes free rein in the dimension normally subject to harmony. In this dissertation, I will examine vowel-to-vowel coarticulatory processes in two harmonizing languages, Hungarian and Tatar, both in stimuli exhibiting dimensional separation from the harmony process (height coarticulation) and stimuli subject to lexical separation (disharmonic items).

When similar processes exist at the phonetic and phonological levels and compete for control of the same set of acoustic cues, the demands of the phonological process generally supersede the natural phonetic inclinations. Such phonetic doublets have been examined with regard to nasalization (Cohn, 1990) and the relationship between stop voicing, pitch, and tone (Francis et al., 2006). Cohn (1990) found that in English, a language without phonological nasalization, gradient nasalization induced by neighboring nasal consonants was allowed to spread freely, while in French, such phonetic nasalization is suppressed in order to maintain a clear division between nasal and oral vowels. A similar relationship accompanies consonant voicing, pitch, and tone: in nontonal languages, onset f0 tends to be higher following voiceless stops than voiced ones (House & Fairbanks, 1953; Lehiste & Peterson, 1961; Löfqvist, Baer, McGarr, & Story, 1989), a perturbation that can persist for up to 100 ms (Hombert, 1978). However, in Cantonese, a tonal language, such phonetic perturbations are restricted to 10 ms or less (Francis et al., 2006), leaving f0 free to act as a cue for tone. These phonetic doublets each possess a shared diachronic origin, wherein the phonological process arises through grammaticalization of its phonetic predecessor due to the loss of a primary cue (such as the deletion of a neighboring nasal consonant or loss of a voicing distinction in stop consonants) (Hajek, 1993; Hombert, Ohala, & Ewan, 1979; Hyman, 1976). Without the primary cue, the secondary cue – vowel nasalization or tone – is elevated to phonological status in order to maintain existing distinctions between similar lexical items. When this occurs, a systematic synchronic relationship persists between the phonetic and phonological processes due to pressure to maintain the integrity of the phonological process.

Another apparent phonetic doublet exists in vowel harmony and vowel-to-vowel coarticulation. Just like the established phonetic doublets of nasalization and consonant voicing, pitch, and tone, harmony and coarticulation share a well-researched diachronic connection. Vowel harmony arises when a particular pattern of coarticulation undergoes phonologization (Majors, 2006; Ohala, 1994b), which is likely driven by listener misperception of phonetic perturbations as phonological (Busa & Ohala, 1998; Ohala, 1994b). However, unlike the established doublets described in Cohn (1990) and Francis et al. (2006), there is no opportunity for harmony and coarticulation to coexist with regard to the same dimension. Harmony completely neutralizes the distinction between vowels with regard to the affected feature, effacing the acoustic and articulatory canvas on which coarticulation would leave its mark. This key difference differentiates harmony and coarticulation substantially from conventional phonetic doublets; indeed, the only methods by which it is possible to examine the synchronic relationship between harmony and coarticulation is by contrasting harmony in one dimension, such as backness, with simultaneous coarticulation in another, such as height. Alternatively, one can examine lexemes that fail to conform to harmony in an otherwise harmonizing language to gauge the direction and magnitude of coarticulation in the dimension that harmony normally operates in. (In Tatar, disharmonic lexemes, like /ʃærɑb/ ‘wine’, are frequently established loan words from Arabic and Persian; in Hungarian, transparent vowels allow stems to combine front and back vowels without violating harmony, as in /ɔki/ ‘who.’) Both methods examine the relationship between the two processes at a remove, asking, in essence, whether the speaker's knowledge of the harmony process in the language spills over into related phonetic processes realized either in separate dimensions or in pockets of the lexicon where harmony is not in force. Because of this lexical or dimensional separation, the synchronic relationship between harmony and coarticulation is fundamentally different from that existing between phonetic and phonological nasalization or phonetic f0 perturbation tied to consonant voicing and historically derived tonal distinctions.

This fundamental difference between harmony and coarticulation and other phonetic doublets makes it difficult to formulate well-informed theoretical predictions. One way of approaching the problem is to ignore the ways in which harmony and coarticulation do not function as a phonetic doublet and frame predictions based on the behavior of other doublets, where phonologized processes suppress their phonetic counterparts. Under this view, harmony may be expected to suppress VV coarticulation, particularly coarticulation paralleling the direction of harmony, leading to a preference for coarticulation in the opposite direction. An alternate approach is to assume that the synchronic relationship between harmony and coarticulation will closely resemble their diachronic connection, leading to a prediction that the directions of harmony and coarticulation will proceed in parallel. In the next section, I will give examples of coarticulation in harmonizing languages that support each of these theories.

1.2. Past research on vowel harmony and VV coarticulation

Despite the inherent challenges of studying coarticulation in harmonizing languages, a growing body of work has examined the synchronic connection between coarticulation and harmony. Beddor and Yavuz (1995) investigated vowel-to-vowel coarticulation in the speech of three native speakers of Turkish, a Turkic language with left-to-right backness harmony, limited rounding harmony, and word-final stress. Their study of real disharmonic words found similar coarticulatory changes to F2 in the anticipatory direction for target and trigger vowels /ɑ/, /i/, and /e/, while carryover coarticulation was restricted to a single target-trigger vowel pair. Thus, the dominant direction of coarticulation opposed the direction of harmony. They speculate that this directional asymmetry in Turkish may be linked either to its harmonic phonological structure or to the presence of word-final stress. These Turkish findings mirror preliminary coarticulatory work on Tatar, a related Turkic language in which strong anticipatory effects on F2 have been found to the exclusion of statistically detectable carryover effects (Conklin, 2015). (However, since this initial study of Tatar coarticulation depended on data provided by a single speaker, it ought to be viewed as preliminary and subject to amendment based on the findings of a larger dataset, such as the one presented here.) Both the Turkish and the preliminary Tatar results support the hypothesis that vowel harmony may have a suppressive effect on its parallel coarticulatory process, just as observed for other phonetic doublets.

Additional studies of vowel-to-vowel coarticulation in harmonizing languages have been conducted in Yoruba (Przezdziecki, 2005), Wolof, and Pulaar (Dye, 2015), all of which exhibit vowel harmony with regard to the feature [ATR]. Przezdziecki (2005) focuses on the diachronic relationship of coarticulation and harmony in three Yoruba dialects that differ with regard to which vowels are affected by ATR harmony. His data reveal that dialects without harmony in high vowels nonetheless exhibit harmony-like patterns of coarticulation for these vowels, buttressing the argument that the diachronic roots of harmony lie in the phonetics of coarticulation. Dye (2015) focused on the synchronic relationship between harmony and coarticulation in two languages with ATR harmony proceeding in opposite directions, Wolof and Pulaar, and found that the principal direction of coarticulation was the same as the direction of harmony in each language. Dye's results contradict the central finding of Beddor & Yavuz (1995), who found that the principal directions of harmony and coarticulation in Turkish were opposite rather than parallel, and support the opposite theory – namely, that harmony and coarticulation should be expected to proceed in parallel.

1.3. Stress and coarticulation

Just as a consistent synchronic relationship between harmony and coarticulation across languages has yet to emerge, so also the connection between prosodic prominence of varying kinds and coarticulation is not uniform. Numerous studies have investigated the relationship between stress and coarticulation, and many have found that stressed syllables exhibit less (or less frequent) VV coarticulation than unstressed ones (Beddor et al., 2002; Farnetani, 1990; Fowler, 1981; Magen, 1984, 1997; Majors, 2006; Mok, 2012; Nicolaidis, 1999; Recasens, 2015). Work investigating the impact of varying levels of prosodic prominence on coarticulation has also found that the higher the degree of prominence, the greater the coarticulatory resistance that is likely to be observed (Cho, 2004; Fletcher, 2004). However, such findings are not uncontradicted: Beddor, Harnsberger, & Lindemann (2002) failed to find coarticulatory asymmetries due to stress in Shona, and Manuel & Krakow (1984) observed greater coarticulation in stressed syllables in Swahili than in unstressed ones. Results from other studies suggest that stress asymmetries may vary by vowel (Majors, 2006) or be mediated by neighboring consonants (Recasens, 2015). Past research on stress and coarticulation is explored in greater detail in Chapter 2; for the present purpose, it is sufficient to note that while stress impacts coarticulation, the relationship is not uniform across languages, segments, or other conditions.

1.4. Stress, coarticulation, and harmony

Stress has not yet been incorporated into studies of vowel harmony and coarticulation in a consistent fashion. Dye's (2015) dissertation contrasted two languages with initial stress and differing directions of harmony, while Beddor & Yavuz (1995) looked at a single language with word-final stress and left-to-right harmony, similar to Tatar, which is examined in this dissertation. Przezdziecki (2005) does not consider stress in his study of Yoruba, writing that it "is not a distinctive feature in Yoruba" (p. 104). A central goal of this dissertation is to investigate the synchronic relationship between stress, vowel harmony, and coarticulation through original data in three languages. This data represents the first study of stress and coarticulation in languages with backness harmony, and the harmony systems under examination here also complement earlier work on the topic, which has focused in large part on systems of ATR harmony (see, e.g., Dye, 2015; Przezdziecki, 2005). Table 1 illustrates the study design embraced here, in which Spanish serves as the sole non-harmonizing language due to its variable placement of stress, providing a view of coarticulation in three different arrangements of stress. (Table 1 does not fully capture the range of Spanish stress examined.) Tatar and Hungarian share similar left-to-right systems of backness harmony, but their stress patterns are opposite: Tatar has word-final stress, while Hungarian stress is word-initial.

Table 1: Languages chosen to fulfill study design

	V_1 stress	V_2 stress
Harmonizing	Hungarian	Tatar
Non-harmonizing	Spanish	Spanish

1.5. Research questions & hypotheses

The primary aim of this dissertation is to determine what, if any, is the cross-linguistic relationship among stress, direction of vowel harmony, and direction and degree of VV coarticulation. Is there synchronic pressure to maintain a parallel between the directions of harmony and coarticulation, regardless of the position of stress, as the data from Dye (2015) suggests? Or does vowel harmony sometimes induce a preference for coarticulation in the opposite direction, as might be expected if harmony and coarticulation formed a typical phonetic doublet and as the data from Beddor & Yavuz (1995) could lead one to believe? A final – and likely – alternative is that coarticulatory direction is not influenced by the direction or presence of harmony, but is determined primarily by synchronic patterns of stress or other unidentified phonological factors. Beddor & Yavuz (1995) acknowledge this possibility, writing that under this interpretation, "once a phonetic behavior is phonologized, it becomes a phenomenon largely distinct from the behavior that gave rise to it." (p. 49) If this proves to be the case, then no relationship will exist between the direction of harmony and direction of coarticulation in harmonizing languages.

In pursuing these questions, I will test five specific hypotheses. The first two are tested in the Spanish study, focusing on the role of stress, distinct from harmony.

Hypothesis 1: Unstressed vowels make better targets of coarticulation than stressed ones.

Hypothesis 2: Stressed vowels make better triggers of coarticulation than unstressed ones.

Hypotheses 3 and 4 relate to Tatar, covering contrasting predictions for the joint impact of stress and harmony on coarticulation.

Hypothesis 3: If maintaining a directional parallel between vowel harmony and coarticulation is a controlling factor in determining coarticulatory direction, carryover coarticulation is expected to outweigh anticipatory coarticulation in Tatar in order to match the left-to-right direction of harmony.

Hypothesis 4: If stress is the strongest predictor of coarticulatory direction, anticipatory coarticulation is expected to outweigh carryover in Tatar in order to preserve word-final stressed vowels as the best triggers and poorest targets of coarticulation.

The final hypotheses predict coarticulatory direction in Hungarian, relying on the assumption that coarticulation will either move outward from the stressed vowel or parallel the direction of harmony (or both). If, however, coarticulation opposes the direction of harmony, but also proceeds outward from the stressed vowel, a mix of the two directions is expected.

Hypothesis 5: If stress is the strongest predictor of coarticulatory direction, carryover coarticulation is expected to outweigh anticipatory in Hungarian in order to preserve word-initial stressed vowels as the best triggers and poorest targets of coarticulation.

Hypothesis 6: If maintaining a directional parallel between vowel harmony and coarticulation is a controlling factor in determining coarticulatory direction, carryover coarticulation is expected to outweigh anticipatory coarticulation in Hungarian in order to match the left-to-right direction of harmony.

While the primary cross-linguistic research questions relate to the directionality of coarticulation across languages, the impact of target and trigger vowel, intervening consonant, and stress on coarticulation within each language will also be considered.

1.6. Structure of the dissertation

The structure of this dissertation is the following: Chapter 2 presents the Spanish study, Chapter 3 contains the Tatar coarticulation study along with an acoustic description of the Tatar vowel space, which has received little attention in previous literature, and Chapter 4 addresses the Hungarian study. The results from all three languages are summarized and synthesized in the Conclusion (Chapter 5).

2. SPANISH

A version of this chapter has been submitted for publication in *Phonetica.*

2.1. Introduction

The goal of this chapter is to examine vowel-to-vowel coarticulation in Spanish, a language without vowel harmony, focusing on how stress and coarticulation interact without the additional influence of vowel harmony. This chapter analyzes the roles of stress, target vowel, and trigger vowel in VV coarticulation in Spanish-like non-words, with special emphasis on the role of stress. Although Spanish makes an optimal test case for studying VV coarticulation, it has been largely overlooked in this respect. Unstressed Spanish vowels are not subject to the phonetic reduction found in other languages, such as English, meaning that the effects of coarticulation are easier to observe. Moreover, stress in Spanish can legitimately fall on any of three syllables in the word and is communicated orthographically by the acute accent mark, making possible the use of carefully designed non-words with pre-determined stress assignment. In this introduction, I will discuss previous research related to the effects of stress, intervening consonant, target vowel, and trigger vowel on the degree and direction of VV coarticulation with the goal of highlighting the need for a better understanding of these factors and the interactions among them.

2.1.1. Effect of stress on VV coarticulation

Several studies have proposed that vowels in lexically stressed syllables undergo coarticulation less frequently or to a lesser extent than their unstressed counterparts (see, e.g., Beddor et al., 2002, Fowler, 1981, Magen, 1984, Majors, 2006, and Magen, 1997 on English; Mok, 2012 on Mandarin and Cantonese; Farnetani, 1990 on Italian; Nicolaidis, 1999 on Greek; Recasens, 2015 on Catalan). Prosodically prominent syllables have also been shown to exhibit increased coarticulatory resistance in proportion to the level of prominence (Cho, 2004; Fletcher, 2004). This coarticulatory resistance has been attributed to the hyperarticulated character of stressed syllables (de Jong, Beckman, & Edwards, 1993), and to the need to maximize the phonetic clarity of the most prominent segments (Cho, 2004).

A great deal of variability in the effect of stress on coarticulation has also been detected in previous research, suggesting that other factors can mediate the effect of stress. For example, Majors (2006) documented a stress-related asymmetry in the coarticulation of English /i/ (but not /o/) for two out of four speakers tested, demonstrating that both target vowel and individual variability can mitigate the effect of stress. How stress influences coarticulatory patterns may also vary across languages: Beddor, Harnsberger, & Lindemann (2002) found stress asymmetries in VV coarticulation in English (a non-tonal, stress-timed language), but not in Shona (a Bantu language with lexical tone), while Manuel & Krakow (1984) showed that stressed targets undergo more coarticulation than unstressed ones in Swahili – an opposite pattern to that recorded in most other languages. Additionally, Recasens's (2015) investigation of the effect of stress on VV coarticulation in Catalan suggested that stress affects the duration and magnitude of coarticulation, but not its direction, which in his results was mediated primarily by the intervening consonant.

In summary, while in some reports stressed syllables appear to be more resistant to coarticulation than unstressed ones, substantial variability associated with speaker, language, target vowel, and intervening consonant complicates the question. Furthermore, the prevalent use of disyllabic stimuli in previous studies evaluating the effect of stress on coarticulation (see, e.g., Beddor & Yavuz, 1995; Majors, 2006; Nicolaidis, 1999; Recasens, 1987) made it difficult to conclude that the effect was due to the presence of stress on a target vowel and not due to the lack of stress on a triggering vowel. (Where stress is fixed, the factors of stress and direction are conflated: in ˈCV.CV stimuli, anticipatory coarticulation is only measured in stressed syllables and carryover coarticulation in unstressed syllables. Similarly, in CV.ˈCV stimuli, anticipatory targets are always unstressed, while carryover targets are stressed. To separate the factors of stress and direction, the design must either include trisyllabic stimuli, as in this chapter, or find a way to avoid adhering to fixed stress patterns.) Among VV coarticulation studies using trisyllabic stimuli, the design of the target words and focus of the study has generally not been on differentiating among the many possible placements of stress (Beddor et al., 2002; Mok, 2011; Renwick, 2012). The present study specifically aims for a thorough and systematic investigation of the effect of stress on VV coarticulation in Spanish - a language where the effects of stress on coarticulation can be largely separated from the effects of stress-dependent qualitative reduction. Building on previous research, the target words were designed to differentiate the effect of stressed targets from that of unstressed triggers. Moreover, the roles of vowel identity and direction of coarticulation are also addressed in conjunction with stress, resulting in a more nuanced depiction of VV coarticulation.

2.1.2. Effect of consonant on VV coarticulation

Previous research suggests that one of the key factors in determining how much two vowels will coarticulate with one another is the identity of the intervening consonant. Non-lingual consonants, such as /p/ and /b/, have generally been found to permit a large degree of VV coarticulation (Fowler & Brancazio, 2000; Modarresi, Sussmann, Lindblom, & Burlingame, 2004), while lingual consonants have often been shown to reduce VV coarticulatory effects. With respect to velars in particular, some studies suggest that more VV coarticulation occurs across velars than across other lingual consonants (see Fowler & Brancazio, 2000 with regard to /g/ and Fletcher, 2004 on /k/), while others indicate that velars block coarticulation (Butcher, 1989). Moreover, among lingual consonants, significant evidence indicates that the degree of articulatory constraint, both of the intervening consonant and of the entire CV_2 sequence, directly impacts coarticulation in that highly constrained sequences coarticulate less (Recasens, 1987, 2002, 2015). The degree of articulatory constraint – the involvement or displacement of a particular articulator needed to produce the segment in question – can vary across languages for similar segments in accordance with the language-specific articulatory profiles of segments. Because of this, corresponding variability can be expected in the degree of VV coarticulation that particular sequences will allow across languages (Modarresi et al., 2004; Recasens, Farnetani, Fontdevila, & Pallarès, 1993). In the present study, I am not directly concerned with the effect of the consonant; however, to make the stimuli more generalizable and to reduce their monotonicity, two consonants with differing articulatory properties, the velar /k/ and the labial /p/, were used. These consonants emerged in much of the previous research as the ones least likely to block VV coarticulation, and were therefore selected in order to capture a wider cross-section of the language while maximizing the study's ability to detect VV coarticulation.

2.1.3. Effect of vowel on VV coarticulation

Another general finding of studies on VV coarticulation concerns the identity of the participating vowels themselves. For example, the high vowel /i/ is often found to be a strong trigger of coarticulation (Beddor & Yavuz, 1995; Butcher & Weiher, 1976), but a comparably poor target (Majors, 2006; Recasens, 1987). Low vowels, on the other hand, have been shown to undergo coarticulation without causing it (see, e.g., Beddor & Yavuz, 1995; Mok, 2011; Recasens, 1987, 2015).

Less is known about coarticulation in mid vowels, which are presumably not subject to the extreme behaviors associated with high and low vowels but could nevertheless exhibit asymmetries based on the direction (anticipatory or carryover) and type (height or backness) of coarticulation. Similarly, it is not clear whether the backness of mid vowels has consequences for a vowel's propensity to coarticulate. Differences in backness leading to differing susceptibility to VV coarticulation in general are not well documented, but Kaun's (1995) typological study of rounding harmony found that front vowels more commonly act as triggers of rounding harmony than back vowels do. Since Kaun examined rounding harmony, this may be no more than a side effect of the well-known way in which roundness naturally reinforces backness acoustically by lowering formant values; however, given the diachronic connection between VV coarticulation and vowel harmony (Ohala, 1994b, 1994a), it is not unreasonable to expect a corresponding division in backness to appear in coarticulation. This chapter examines two mid vowels of comparable height but differing backness in order to determine whether they are affected by VV coarticulation to the same extent and in the same direction.

2.1.4. Direction of coarticulation

VV coarticulation can proceed in two different directions: anticipatory, occurring when a preceding vowel assimilates to the following one, and carryover, when a following vowel assimilates to the preceding one. Fundamentally different mechanisms are believed to underlie the two directions of coarticulation. Carryover coarticulation is sometimes considered primarily a biomechanical effect, while anticipatory coarticulation may also have a cognitive component and occur in part due to advance planning (Henke, 1966; Whalen, 1990). Thus, at the heart of any study of the two directions of coarticulation is an underlying tension between physical limitations and cognitive constraints.

The asymmetry between anticipatory and carryover coarticulation is not limited only to their underlying mechanisms; they also exhibit an asymmetrical distribution across languages. Anticipatory VV coarticulation is dominant in some languages, while carryover coarticulation is prevalent in others. For example, studies of English VV coarticulation consistently uncover strong carryover effects (see, e.g., Beddor et al., 2002; Bell-Berti & Harris, 1976, p.; Manuel & Krakow, 1984), while stronger anticipatory effects have been found in many other languages, including Shona (Beddor et al., 2002; Manuel & Krakow, 1984), Swahili (Manuel & Krakow, 1984), and Turkish (Beddor & Yavuz, 1995). The causes of these crosslinguistic differences are not fully understood, although one potentially explanatory factor is the location of stress, particularly in languages with fixed stress. Given the potential resistance of stressed vowels to coarticulation, languages with fixed final stress can be expected to exhibit more anticipatory than carryover coarticulation. Additionally, consonantal restrictions on tongue-dorsum movements associated with particular segments can block or facilitate coarticulation in a particular direction (Recasens, 2002; Recasens, Pallarès, & Fontdevila, 1997). Thus, stress, vowel and consonant inventories, and the language-specific phonetic properties of individual segments jointly guide the general coarticulatory trends of a language.

2.1.5. Interactions among factors

While previous research has addressed the roles of stress, vowel identity, and direction in coarticulation, few studies have investigated their combined effects. One of the specific contributions of the study presented in this chapter is that it affords the opportunity to examine the effect of stress in combination with the effects of other factors simultaneously. This study is also one of the first investigations of Spanish coarticulation to present data from a broad base of speakers. For example, Recasens' (1987) study examined two speakers of Spanish, while Henriksen (2017) reported only on anticipatory assimilation from 24 speakers. This chapter expands the body of research on Spanish coarticulation by examining both the anticipatory and carryover directions of coarticulation in data from 20 participants. Moreover, the in-depth investigation of the interactions between stress, vowel identity, and coarticulatory direction offered here will help determine whether the findings of similar studies (such as Recasens, 2015 on Catalan) are generalizable to other languages, such as Spanish, as well as to different sets of vowels. Finally, the data offered by this study will help solidify our understanding of the role of stress in governing patterns of VV coarticulation, laying the groundwork for an examination of stress, vowel harmony, and coarticulation in Tatar and Hungarian in Chapters 3 and 4.

2.1.6. Spanish and its vowel system

Spanish was chosen as the target language for this chapter due to several convenient properties of its phonological system. First, Spanish vowels do not undergo extensive phonetic reduction in unstressed position, which characterizes languages like English and Russian (Hualde, 2012). Second, the Spanish vowel system is relatively small and conveniently symmetric, with two front and two back vowels at comparable levels of height, in addition to a single low vowel: /i, e, a, o, u/. Bradlow (1995) reports mean formant values in Hertz for four male speakers of Madrid Spanish (represented in Figure 1), sketching a roughly symmetrical vowel space where progressively higher vowels are articulated further forward (for front vowels) or back (for back vowels) than their lower counterparts. The Spanish mid vowels /e/ and /o/ in particular provide a suitable basis for comparing VV coarticulation in back versus front vowels, where both are comparable in terms of height. Using /o/ as a trigger for /e/ and /e/ as a trigger for /o/ ensures that coarticulation will be limited to the combined F2 dimension of backness and roundness.

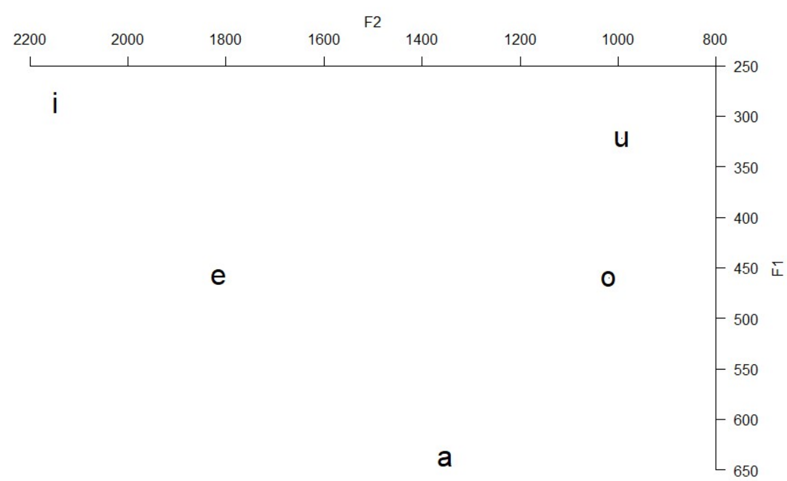

Figure 1: Spanish vowel space (based on mean formant values reported in Bradlow (1995, p. 1918).

2.1.7. Hypotheses and study design

The design of this study aimed to isolate the effects of stress placement and target vowel identity in determining the magnitude and direction of VV coarticulation, testing two hypotheses.

Hypothesis 1: Unstressed vowels make better targets of coarticulation than stressed ones.

Hypothesis 2: Stressed vowels are better triggers of coarticulation than unstressed ones.

Together, these hypotheses predict the following order of coarticulatory magnitude: Stressed trigger > unstressed target and trigger > stressed target. To test these hypotheses, this chapter relies on specially designed sets of Spanish-like non-words that vary minimally with regard to stress and target vowel. To test the first hypothesis, this study compares the coarticulatory results of all phonologically possible combinations of stressed and unstressed trigger vowels with stressed and unstressed target vowels. The trisyllabic design also allowed me to address the second hypothesis, examining whether stressed vowels are better triggers of coarticulation than unstressed ones. With the trisyllabic stimuli, it was possible to disambiguate the effect of a stressed target from that of an unstressed trigger, providing further clarification to the results of previous studies that investigated stress effects on coarticulation without making this distinction in disyllables (Beddor & Yavuz, 1995; Majors, 2006; Nicolaidis, 1999; Recasens, 1987).

To assess coarticulatory differences in each of the conditions listed above, I analyzed second formant frequency (F2) of the target vowels in the speech of twenty native speakers of Spanish. (Due to space and time constraints, F1 was not analyzed for Spanish.) Because of this relatively large sample size, this study has the benefit of capturing a wide cross-section of the coarticulatory variation present across individuals and minimizing the impact of subject-related variability. In the next section, I describe in detail the methods used to determine the degree and direction of coarticulation resulting from the effects of stress placement and vowel identity.

2.2. Methods

2.2.1. Participants

Twenty native Spanish speakers (F=12; M = 8) aged 19 – 50 (M = 30.7; SD = 8.2) completed the study; thirteen participants were from Colombia, three from Mexico, and one each from Spain, Ecuador, Honduras, and Peru. While this dialectal diversity may introduce additional variability to the study, it was not viewed as grounds for turning participants away. Rather, as the dialects in question all share a five-vowel inventory with similar overall spacing (Canfield, 1981; Chládková, Escudero, & Boersma, 2011; Dabkowski, 2018; Holliday & Martin, 2018; Lipski, 1987, 1994; Vera Diettes, 2014), it enhances the generalizability of the results.[2] Given that the study was conducted in the United States, all participants were bilingual in English and all resided in the United States at the time of the study. Average length of residence in an English-speaking area was 3.7 years at the time of the study, ranging from 6 months to 8 years. Knowledge of English was unavoidable under the circumstances, and it must be acknowledged that it could have potentially influenced the patterns of VV coarticulation observed for these participants. However, given our limited knowledge of the way coarticulatory patterns interact in second language learning (see, for example, Kondo, 2000), the probability and exact nature of the potential influence of L2 is difficult to determine.

Nine participants reported knowledge of languages other than Spanish and English, including Italian, French, German, Portuguese, and Mandarin, but no participant used a third language extensively. All participants reported Spanish as their first acquired and most dominant language on a self-report survey. Participants reported no speech, hearing, or language impairments, and all participants were compensated for their time.

2.2.2. Target words

Target items and fillers were three-syllable Spanish-like non-words with stress on the first, second, or third syllable of the word, listed in Appendix A. (Each target word appeared in each stress condition.) This variable stress placement was possible because Spanish orthography marks unpredictable stress with an acute accent mark. Target words had the form $CV_1CV_2CV_3$, where all three consonants were either /k/ or /p/, and the target vowel under analysis was always V_2; an example target word is /keˈkeko/, which tests the anticipatory influence of /o/ on /e/. Placing the target syllable in the second position insulated it, at least in part, from coarticulatory effects from beyond the target word. Two target vowels, /e/ and /o/, were tested. With regard to consonants, stops were chosen because of the relative ease with which the boundary between

[2] One participant came from Mexico City, Mexico, an area that has been noted to exhibit reduction and variation in unstressed vowels (Dabkowski, 2018; Lipski, 1994). Dabkowski (2018) found that the reduction of unstressed vowels in Mexico City Spanish consisted primarily of shortening and changes to voice quality, but did not significantly affect vowel formants. Because of this, there was not judged to be sufficient reason to exclude the participant, and their data was included in the analysis. Similarly, some regional allophonic variation in the openness of /e/ and /o/ is reported for Honduran Spanish in Lipski (1987), but as this minimal change is restricted to closed syllables and pre-rhotic contexts, it is not at play in my target words.

consonant and vowel can be identified; voiceless stops were chosen because voiced stops undergo intervocalic spirantization in Spanish.

Some of the target words were designed as controls; in these items, all three vowels were identical – for example, /keˈkeke/ or /poˈpopo/ (the canonical form). In order to trigger carryover coarticulation, the trigger vowel V_1 in the first syllable was changed; to measure anticipatory coarticulation, V_3 was changed. Thus, /koˈkeke/ creates the conditions needed for the carryover effect of unstressed /o/ (V_1) on stressed /e/ (V_2) when compared to /keˈkeke/, while /keˈkeko/ creates the conditions for the anticipatory effect of unstressed /o/ (V_3) on stressed /e/ (V_2). Only one trigger vowel at a time was changed per item; the vowel that was neither trigger nor target was identical to the target vowel in all stimuli. The vowels /e/ and /o/ served as both trigger and target vowels. Each target word was repeated with stress in every possible location, thus testing the effect of an unstressed trigger on a stressed target (e.g. /koˈkeke/), the effect of a stressed trigger on an unstressed target, (e.g. /ˈkokeke/), and the effect of an unstressed trigger on an unstressed target, (e.g. /kokeˈke/), in both the anticipatory and carryover directions for a total of 36 target words (three trigger conditions (preceding trigger, following trigger, canonical or no trigger) * two target vowels * two consonantal environments * three stress locations). Additionally, 84 fillers were included as distractor items. All target words and fillers were read in random order three times. Thus, each subject read a total of 360 items.

2.2.3. Procedure

Participants completed a language background questionnaire and a production task in which they read non-words embedded in ten carrier phrases, as shown in (1).

(1) Quien ganó el ______ por la mañana fue Carlos.
It was Carlos who won the _________ this morning.

Carrier phrases were randomized across trials. (All ten carrier phrases are shown in Appendix B.) The structure of the phrases was selected to avoid placing undue prosodic prominence on the target items, instead placing narrow focus on the final proper name. This strategy was successful to a degree, although target words still received varying degrees of prosodic emphasis due to their unfamiliarity.

Target words were blocked, randomized, and mixed with filler non-words at a 1:2.3 ratio. Fillers, like targets, were three-syllable, Spanish-like nonsense words, but exhibited greater phonological variety than targets. One hundred eight target tokens were presented to each participant. Participants were informed that stress would be marked in relatively unusual positions on the non-words (typically, stress in Spanish words falls on the penultimate syllable) and encouraged to repeat sentences as necessary until they were satisfied with the naturalness, accuracy, and fluency of their production. One hundred ninety-five productions were discarded during the annotation stage due to disfluencies, speech errors, incorrect placement of stress, or weak formants. An additional 228 items were discarded post-annotation for similar reasons, for a total of 423 excluded items (19.5% of all target items). To verify my judgments about the location of stress, three linear mixed model analyses were computed with Vowel Duration, Vowel f0 at midpoint, and Vowel Intensity at midpoint as the dependent variables, Stress (Stressed versus Unstressed) and Inclusion (Included in Analysis versus Excluded from Analysis) as fixed factors, and Subject as a random factor. These analyses compared the stressed and unstressed target vowels deemed suitable for inclusion to the 228 items excluded post-annotation. The interaction between Stress and Inclusion was significant in each model ($F(1, 1932.650) = 16.501$, $p < .001$ for f0, $F(1, 1944.655) = 10.432$, $p = .001$ for Intensity, and $F(1,1945.553) = 285.815$, $p < .001$ for Duration). Post-hoc analyses with Bonferroni correction showed that f0 and Intensity differed significantly between the two conditions of Stress in those stimuli included for analysis (N = 1737), such that stressed vowels had greater intensity and higher f0 than unstressed vowels, but not those excluded (N = 228). Duration differentiated Stress for both included and excluded utterances (see Table 2), but the difference in means was notably greater and in the expected direction for included utterances (33 ms) compared to excluded ones (-5 ms). Thus, target words excluded from analysis were ambiguous with regard to one or more of the three known acoustic correlates of stress – duration, intensity, and f0. Since none of these correlates corresponds directly or uniquely to stress, the final decision rested on my judgment.

Table 2: Mean duration of stressed and unstressed vowels relative to inclusion in Spanish analysis

	Included	Excluded
Stressed	93.3 ms	69.6 ms
Unstressed	59.9 ms	74.6 ms
Difference	33.4 ms	-5.0 ms

Because a relatively high rate of data loss occurred due to stress misallocation, a structural change to the procedure was made after nine participants. While the first nine participants encountered stimuli with stress on any of three syllables within the same block, the remaining eleven subjects were presented with stimuli blocked by stress location. The order of blocks was counterbalanced across participants to counteract any effects of presentation order. The new procedure raised the mean number of usable tokens produced per participant from 80 to 92 tokens (an average increase of 15%).

Stimuli were presented using the E-Prime 2.0 software (Schneider, Eschman, & Zuccolotto, 2002), with sentences shown in black font on a white screen. Participants proceeded through the task at their own pace. Sessions were recorded in a sound-attenuated room using an Audio-Technica AE4100 cardioid microphone connected directly to a PC via a TubeMP preamp and were digitized at a sampling rate of 44.1 kHz with 16 bit quantization. Recording sessions lasted between 45 and 90 minutes, and breaks were offered every 40 sentences to prevent fatigue effects.

2.2.4. Measurements

Target vowels were annotated in Praat (Boersma & Weenink, 2017) using the onset and cessation of periodicity as the identifying criterion of the transition between vowel and consonant. First and second formant frequency values were extracted at vowel midpoint and 10% of vowel duration from the vowel edge nearest the trigger vowel using Praat's Burg LPC-based algorithm. (Thus, in anticipatory scenarios, vowel edge measurements occurred at 90% of the vowel's duration after onset, but in carryover conditions at 10%.) F2 measurements were used to assess coarticulation in backness, and F1 measurements were used to normalize F2 values. Individual LPC measurements were checked visually; where they did not align with the visible formant, they were corrected by hand. Once extracted, formant values were normalized to reduce the effect of anatomical variation across speakers using log-additive regression normalization (Barreda & Nearey, 2017). Log-additive regression normalization was chosen because it was designed for datasets with missing and unbalanced data, such as the dataset in this study.

2.2.5. Analysis

2.2.5.1. Models detecting coarticulation

Linear mixed models comparing coarticulated and canonical target words (e.g., /koˈkeke/ and /keˈkeke/, respectively) were used to detect VV coarticulation and the impact of stress on coarticulation (implemented in SPSS 25, IBM Corp, 2017). Each model included Stress (Target Stressed, Trigger Stressed, or Neither Target nor Trigger Stressed), Target (/e/ or /o/), and Trigger (/e/ or /o/) as fixed factors, as well as two-way Target by Trigger and Stress by Trigger interactions and a three-way Stress by Target by Trigger interaction.

A significant two-way Target by Trigger interaction would indicate that the magnitude of coarticulation differs by trigger-target pair (/e/ affecting /o/ versus /o/ affecting /e/), while a significant Stress by Trigger interaction would denote consistent differences in coarticulation (across target vowels) due to stress. A significant three-way Stress by Target by Trigger interaction would further suggest that the magnitude of coarticulation depends not only on the trigger-target pair but also on the location of the stress with respect to the coarticulating vowels.

Different directions of coarticulation (anticipatory and carryover) and measurement time points (midpoint and edge) were analyzed in separate models. Log-additive regression normalized second formant frequency (F2) was used as the dependent variable in all analyses, serving as an estimate of the difference in backness (and concomitant rounding).

A random intercept for Subject was also included in each model. Item was not included as a random factor because all the experimental items had very similar structure and thus were not expected to generate significant variability in production. This exclusion also allowed for a reduction of the complexity of the models and minimized the possibility of model-overfitting (Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017).

The main effects of Stress and Target are not of great interest since they only provide information about the general effect of stress and vowel identity on the second formant frequency of the target vowel. The main effect of Trigger is of central importance, since it indicates the presence of coarticulatory effects: trigger /o/ is expected to lower F2, moving the target vowel backwards in the vowel space, while trigger /e/ is expected to raise F2, fronting the target vowel.

Models were separated by direction because the factors Direction (Anticipatory or Carryover) and Stress (Trigger Stressed, Target Stressed, or Neither Stressed) would be in conflict if combined in a single model. If these models were combined, canonical words with second-syllable stress, like /keˈkeke/, would need to serve simultaneously as controls for anticipatory targets like /keˈkeko/ and carryover targets like /koˈkeke/, creating serious difficulties in data analysis and the interpretation of results. Finally, models were separated by time point in order to facilitate model convergence, with values taken at midpoint separated from those taken at vowel edge. Thus, four models were computed: Anticipatory Midpoint, Carryover Midpoint, Anticipatory Edge, and Carryover Edge. Appendix D provides a transcript of the SPSS code used for these models.

2.2.5.2. Model evaluating magnitude of coarticulation

An additional linear mixed model was fitted that implemented a different way of evaluating significant differences in magnitude of coarticulation across conditions. The benefit of this model, which used differences in normalized F2 between the canonical and control conditions as its dependent variable, lay in its ability to analyze changes to the magnitude of coarticulation. Canonical F2 means were calculated for each speaker's target vowels by averaging all relevant utterances. The difference between each F2 value and the relevant canonical mean was then calculated such that the difference score was positive if the change was in the expected coarticulatory direction and negative if the change was in the dissimilatory direction (or close to 0 if there was little change). This is depicted mathematically in (2), where i represents each non-canonical observation of a given vowel and speaker and j represents each canonical observation for the same vowel and speaker.

(2) $F2_i - \frac{\sum F2_j}{n_{F2_j}}$

This approach allowed a direct comparison of the magnitude of coarticulation across coarticulatory directions, consonants, time points, stress conditions, and target vowels. Each of these was used as fixed factors in the model, along with a random factor of Subject. Consonant, which was excluded from the initial models to simplify them, was included here to create a contrast to the non-magnitude models and ensure no effects were missed by the other models due to consonantal interference. Finally, numerous interactions were included, as shown in Table 3.

Table 3: Effects and interactions included in Spanish magnitude model

Main effects	• Stress • Target • Direction	• Time Point • Consonant
Two-Way Interactions	• Stress by Consonant • Target by Consonant • Direction by Consonant • Time Point by Consonant • Target by Direction	• Stress by Target • Stress by Direction • Target by Time Point • Direction by Time Point
Three-Way Interactions	• Target by Stress by Direction • Stress by Target by Consonant	• Target by Direction by Consonant • Target by Time Point by Consonant

2.3. Results

Results are reported by model, beginning with the models designed to detect anticipatory coarticulation (at vowel edge and vowel midpoint, § 2.3.2), followed by carryover models for each time point (§ 2.3.3), and ending with the magnitude model (§ 2.3.4). § 2.3.1 examines the impact of the change in blocking procedure and § 2.3.5 summarizes the effects discussed in

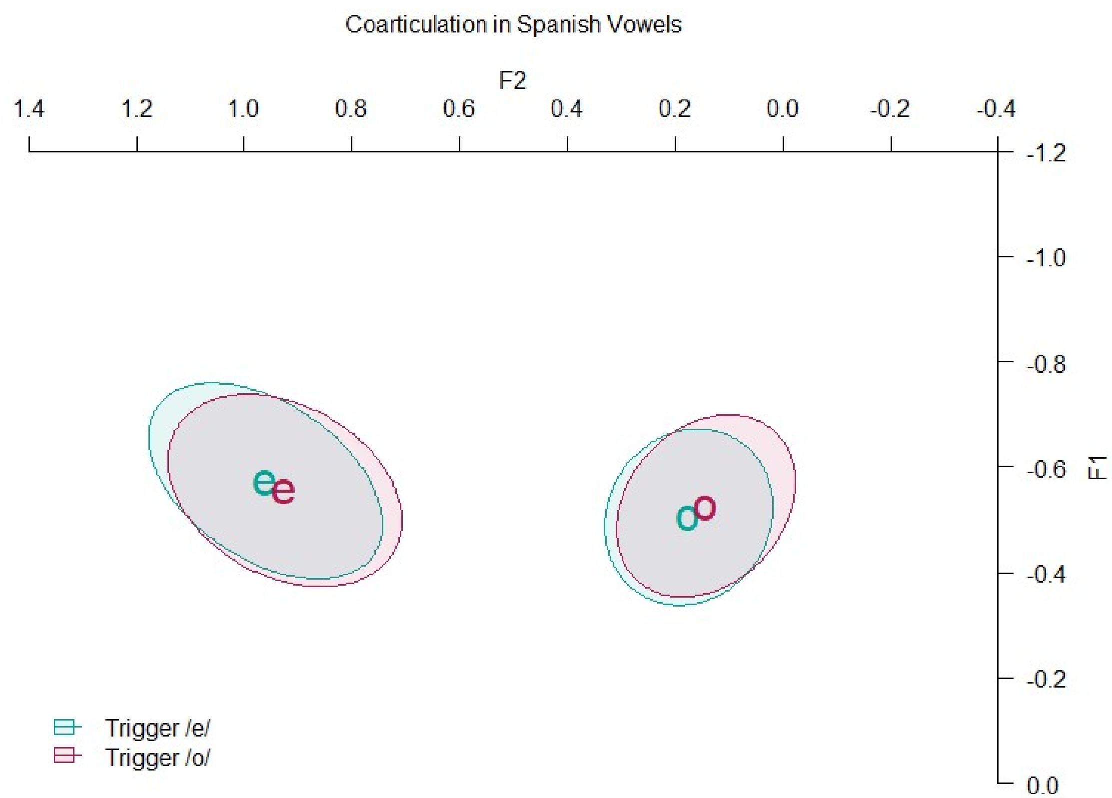

Figure 2: Coarticulation in Spanish vowels in normalized values with 68% confidence ellipses. Canonical /e/ is green, while canonical /o/ is red.

previous sections. All post-hoc analyses were conducted with Bonferroni correction. Figure 2 gives a broad overview of the coarticulatory effects of Target and Trigger in the present data to provide context for the results to be reported.

2.3.1. No impact of blocking procedure

In order to test if the change from fully randomized blocking to blocking by stress in the experimental procedure produced a substantial impact on the results (see § 2.2.3), the anticipatory and carryover models were each computed separately on the results from the two blocking procedures, and the outcomes were compared to the models for the full set of subjects. While some patterns were less robust in the models for individual blocking procedures, as expected with fewer subjects and therefore less power, no new coarticulatory trends emerged. Therefore, I concluded that the change to the blocking procedure did not have a substantial impact on the results and proceed to report the data from all subjects together. All results presented in this section are from models including all twenty participants, with no separation between subjects based on blocking procedure.

2.3.2. Anticipatory coarticulation

2.3.2.1. At vowel edge

In the F2 model for anticipatory coarticulation at vowel edge, main effects indicated that vowel acoustics across conditions were impacted by stress, vowel identity, and VV coarticulation. Significant main effects were present for Stress ($F(2, 1158.901) = 3.810$, $p = .022$), Target ($F(1, 1149.919) = 12{,}344.828$, $p < .001$), and Trigger ($F(1, 1150.221) = 25.527$, $p < .001$). The effects of Stress and Target demonstrate the impact of stress and vowel identity on vowel acoustics, while the main effect of Trigger provides evidence of significant coarticulation in the data, showing that anticipatory coarticulation was present at the vowel edge closest to the following trigger vowel. The interaction between Target and Trigger was not significant ($F(1, 1150.072) = 0.252$, $p = .616$), indicating that no difference in the magnitude of coarticulation was detected across target vowels in this model. (See Figure 3.)

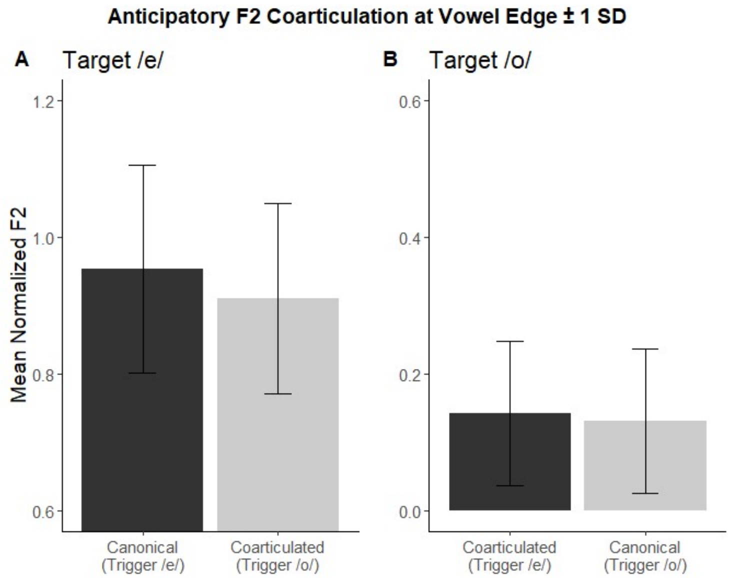

Figure 3: Mean normalized F2 by Target and Trigger for the anticipatory model at vowel edge in Spanish. The difference between the two bars of each panel shows the average magnitude of coarticulation. Canonical vowels appear when the target and trigger are identical (the leftmost bar in panel A and rightmost in panel B.) The two y-axes are set to the same scale, but different range, in order to visually enhance coarticulation; this adjustment reduces the visual difference in backness across target vowels. Error bars display one standard deviation above and below the mean.

In addition to detecting coarticulation between /e/ and /o/, my primary interest is in distinguishing differences in the degree of coarticulation under differing conditions of stress. By using trisyllabic stimuli, I tested three stress conditions: stress fell either on the target vowel (V_2), the trigger vowel (for anticipatory coarticulation, V_3), or the remaining vowel, referred to as "Neither Trigger nor Target Stressed" (for anticipatory coarticulation, this was V_1, which was always identical to the target). The two-way interaction between Stress and Trigger was not significant ($F(2, 1148.946) = 0.111$, $p = .895$), but the three-way interaction between Stress, Target, and Trigger was ($F(4, 1150.391) = 4.712$, $p = .001$), suggesting that the effect of stress on coarticulation was dependent on target vowel. This interaction justified a closer look at the coarticulatory behavior of the two targets under different stress conditions. Post-hoc tests were used to check for the effect of Target for each vowel in each stress condition, and significant or near-significant coarticulation for target /e/ was detected under all three conditions of Stress.

For target /o/, although all coarticulated vowels moved on average in the expected direction, significant coarticulation was detected only in the Trigger Stressed condition. Means and standard deviation for each of these conditions are depicted graphically in Figure 4. These

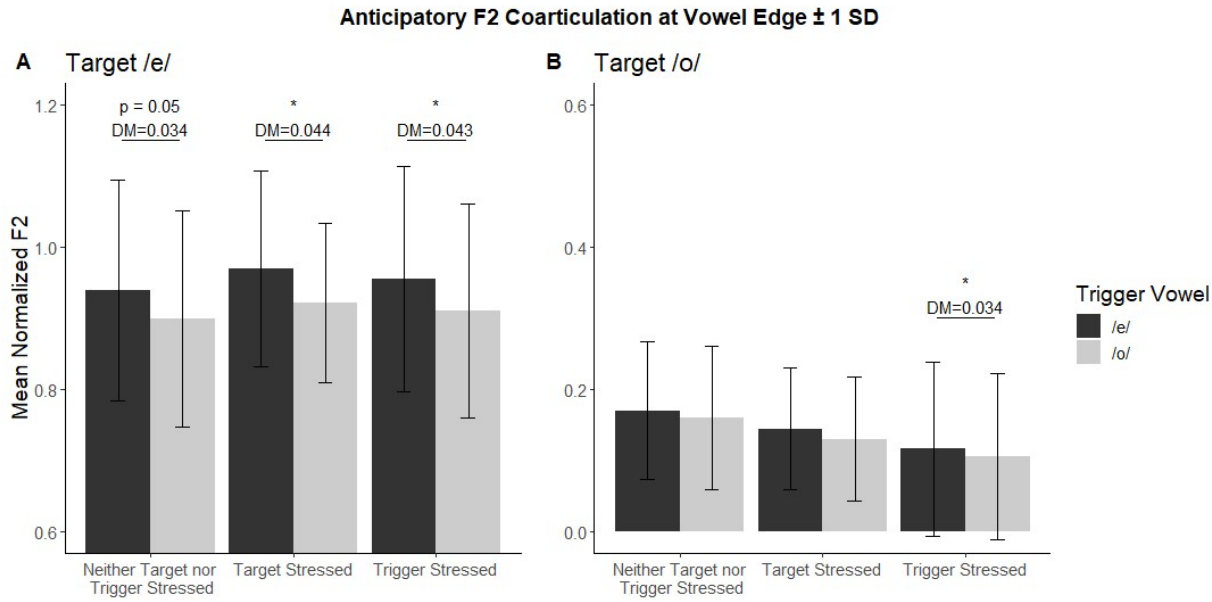

Figure 4: A: Target /e/; B: Target /o/. Mean normalized F2 by Stress and Trigger for the anticipatory model at vowel edge in Spanish. The difference between the dark and light bars shows the average magnitude of coarticulation. Canonical /e/ is represented with dark bars and canonical /o/ with light bars. Error bars display one standard deviation above and below the mean. The two y-axes are set to the same scale, but different range, in order to visually enhance coarticulation; this adjustment reduces the visual difference in backness across target vowels. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$.

results suggest that the location of stress did not have a strong impact on anticipatory coarticulation in /e/, but did influence anticipatory coarticulation in /o/, which was conditional on the stressed trigger.

2.3.2.2. At vowel midpoint

Coarticulation was not widespread in the anticipatory midpoint model. Stress placement and target vowel identity had significant impacts on vowel acoustics, but trigger vowel identity did not. The lack of Trigger significance indicates that, generally, vowel-to-vowel coarticulatory effects in the anticipatory direction did not extend to vowel midpoint. The statistical results of the model for anticipatory coarticulation at vowel midpoint showed a significant main effect for Stress ($F(2, 1157.003) = 9.818$, $p < .001$) and Target ($F(1, 1150.323) = 18{,}557.360$, $p < .001$), but not for Trigger ($F(1, 1150.589) = 0.065$, $p = .798$). The interaction between Target Vowel and Trigger Vowel was also not significant ($F(1, 1150.377) = 1.348$, $p = .246$), nor was the Stress by Trigger Vowel interaction ($F(2, 1149.703) = 0.528$, $p = .590$); however, the three-way interaction between Stress, Target Vowel, and Trigger Vowel was significant (F(, 1150.627) = 4.896, p = .001). However, the post-hoc pairwise comparisons testing for coarticulation in each combination of levels of Stress and Target for this three-way interaction yielded no significant results. This is consistent with the overall finding that anticipatory coarticulation did not extend to vowel midpoint and suggests that the significance of the three-way interaction was not due to changes to coarticulation across Stress conditions.

2.3.3. Carryover coarticulation

2.3.3.1. At vowel edge

In the model examining carryover coarticulation at vowel edge, coarticulation was found in both target vowels, generally with greater magnitudes than in the anticipatory condition. The main effects of Stress (F(2, 1139.946) = 4.696, p = .009), Target (F(1, 1127.328) = 9657.429, p <

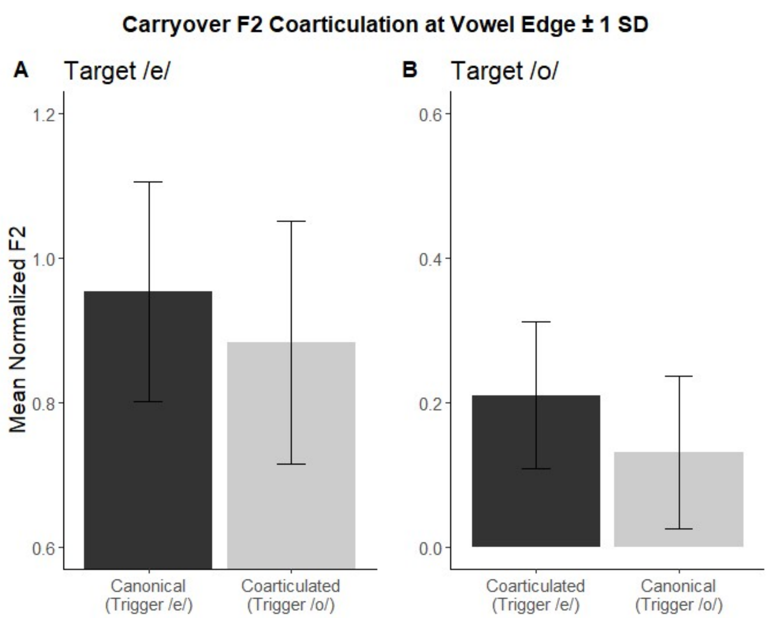

Figure 5: Mean normalized F2 by Target and Trigger for the carryover model at vowel edge in Spanish. The difference between the two bars of each panel shows the average magnitude of coarticulation. Canonical vowels appear when the target and trigger are identical (the leftmost bar in panel A and rightmost in panel B.) The two y-axes are set to the same scale, but different range, in order to visually enhance coarticulation; this adjustment reduces the visual difference in backness across target vowels. Error bars display one standard deviation above and below the mean.

.001), and Trigger (F(1, 1127.792) = 77.151, p < .001) were significant, while the interaction between Target and Trigger was not significant (F (1, 1128.571) = 1.255, p = .263). The significant effect of Trigger indicates the presence of significant coarticulation across both target vowels, /e/ and /o/, and the lack of a significant Target-Trigger interaction suggests that the magnitude of coarticulation did not differ significantly between targets /e/ and /o/. The differences of means for each target vowel (0.075 for target /e/ and 0.058 for target /o/), displayed in Figure 5, were larger than the differences of means in anticipatory coarticulation found under similar conditions, suggesting that the magnitude of carryover effects at vowel edge is greater than the magnitude of anticipatory effects at vowel edge. I will revisit this difference in § 2.3.4 when interpreting the magnitude model.

The two-way interaction between Stress and Trigger was not significant (F(2, 1127.662) = 1.481, p = .228), but the three-way interaction between Stress, Target, and Trigger was (F (4, 1130.604) = 7.322, p < .001), and pairwise comparisons found a significant effect of Trigger for each combination of Target and Stress. The significance of the three-way interaction suggests

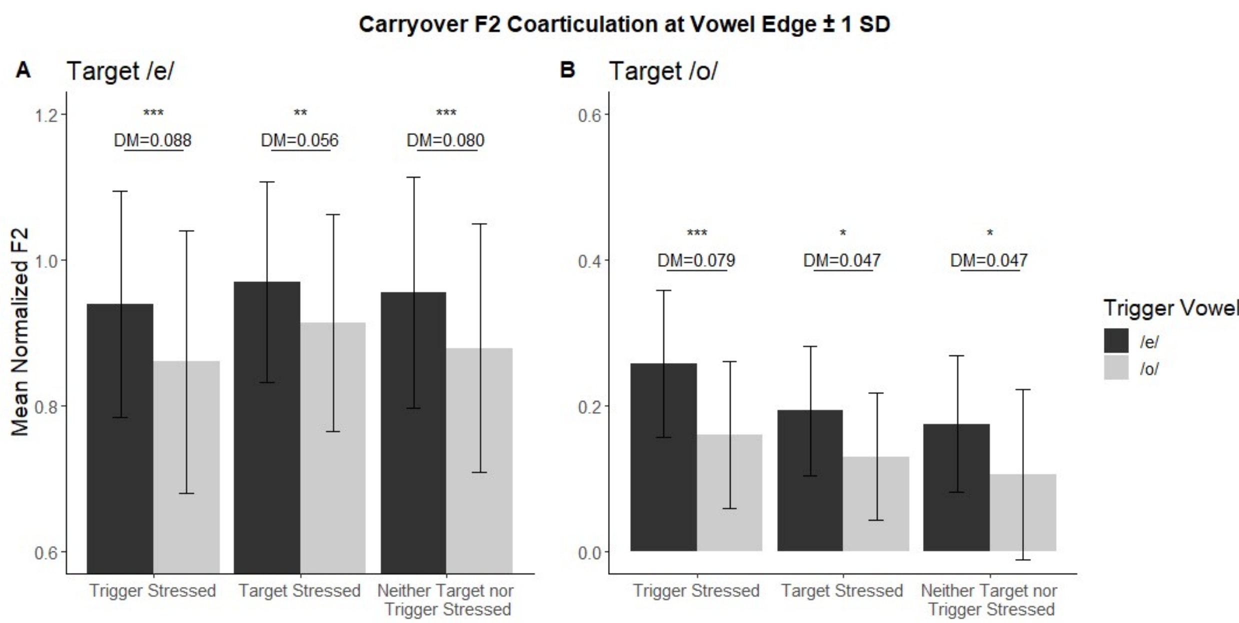

Figure 6: A: Target /e/; B: Target /o/. Mean normalized F2 by Stress and Trigger for the carryover model at vowel edge in Spanish. The difference between the dark and light bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. The two y-axes are set to the same scale, but different range, in order to visually enhance coarticulation; this adjustment reduces the visual difference in backness across target vowels. *** indicates p < .001, ** indicates p < .01, and * indicates p < .05.

that the effect of stress on the degree of coarticulation differed by target, and the pairwise comparisons indicate that coarticulation was present in each case. The varying differences in means found across conditions, reported in Table 4, imply differing magnitude: the strongest coarticulation was induced by stressed triggers, while the weakest was undergone by stressed targets. Coarticulation between unstressed triggers and targets varied, generally occupying the intermediate position. These differences will be further explored in § 2.3.4.

Table 4: Post-hoc results of Stress by Target by Trigger interaction for carryover coarticulation at vowel edge in Spanish. *** indicates p < .001, ** indicates p < .01, and * indicates p < .05.

Target Vowel	Stress	Significance	Difference in Means
Target /e/	Trigger Stressed	***	0.088
	Neither Stressed	***	0.08
	Target Stressed	**	0.056
Target /o/	Trigger Stressed	***	0.079
	Neither Stressed	*	0.047
	Target Stressed	*	0.047

2.3.3.2. At vowel midpoint

As in the carryover edge model, vowel acoustics were significantly impacted by stress, target vowel identity, and VV coarticulation, and the magnitude of coarticulation was generally consistent across target vowels. Statistically, this meant that the main effects of Stress ($F(2, 1139.746) = 13.329$, $p < .001$), Target ($F(1, 1130.521) = 15{,}272.626$, $p < .001$), and Trigger ($F(1, 1130.879) = 25.739$, $p < .001$) were significant for carryover coarticulation at vowel midpoint, and the interaction between Target and Trigger was not significant ($F(1, 1131.358) = 0.716$, $p = .398$). The lack of significance in the Target by Trigger interaction suggests that, overall, the magnitude of coarticulation was comparable across the two target vowels, as shown in Figure 7, which displays the mean normalized F2 for each condition of Trigger for both target vowels. This demonstrates that carryover coarticulation is not limited to the vowel edge closest to the trigger vowel, instead extending at least to vowel midpoint.

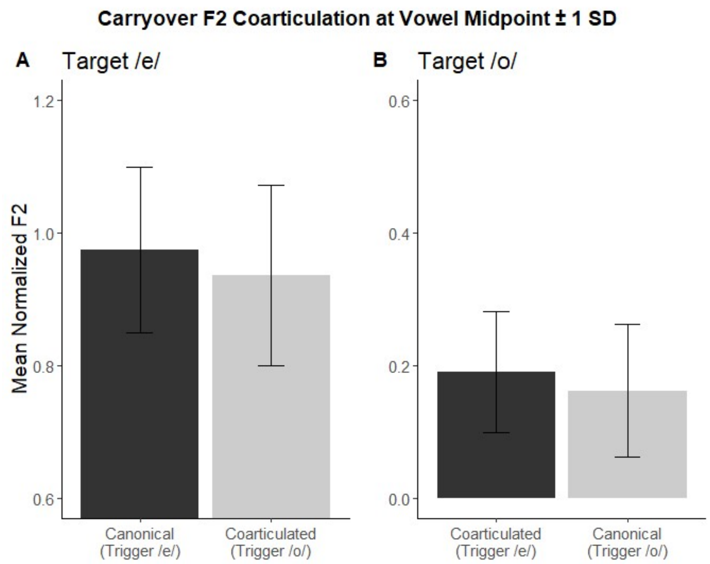

Figure 7: Mean normalized F2 by Target and Trigger for the carryover model at vowel midpoint in Spanish. The difference between the two bars of each panel shows the average magnitude of coarticulation. Canonical vowels appear when the target and trigger are identical (the leftmost bar in panel A and rightmost in panel B.) The two y-axes are set to the same scale, but different range, in order to visually enhance coarticulation; this adjustment reduces the visual difference in backness across target vowels. Error bars display one standard deviation above and below the mean.

As in the edge model, the magnitude of coarticulation was modulated by stress in different ways across the two target vowels. This difference was demonstrated by the outcomes from two interactions and their associated post-hoc pairwise comparisons: the two-way interaction between Stress and Trigger was not significant ($F(2, 1130.802) = 1.675$, $p = .188$), while the three-way interaction of Stress, Trigger, and Target was ($F(4, 1132.690) = 7.211$, $p < .001$). Post-hoc analyses point to significant coarticulation for target /o/ in the Trigger Stressed condition and target /e/ in the Trigger Stressed and Neither Stressed conditions. Thus, stress moderated the magnitude of coarticulation in different ways across the two targets: sustained carryover coarticulation in /o/ was conditional on a stressed trigger, while sustained coarticulation in /e/ occurred under more varied stress conditions. Neither vowel coarticulated at midpoint when stressed. The means and significance of pairwise comparisons across stress conditions and target vowels are displayed visually in Figure 8.

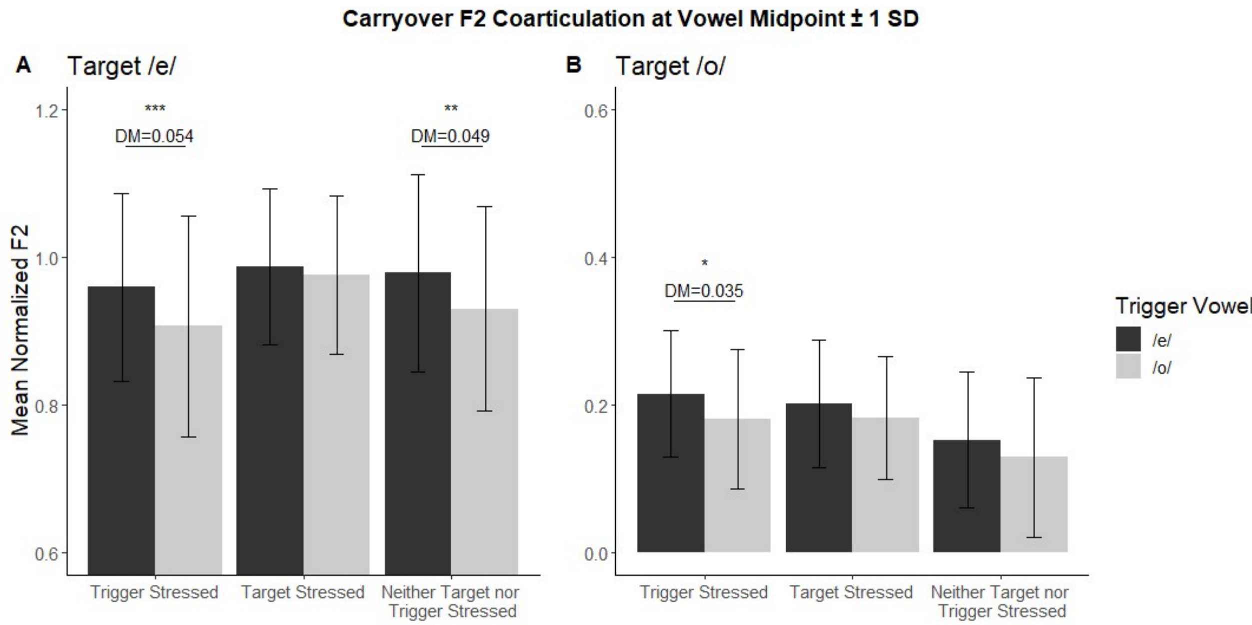

Figure 8: A: Target /e/; B: Target /o/. Mean normalized F2 by Stress and Trigger for the carryover model at vowel midpoint in Spanish. The difference between the dark and light bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. The two y-axes are set to the same scale, but different range, in order to visually enhance coarticulation; this adjustment reduces the visual difference in backness across target vowels. *** indicates p < .001, ** indicates p < .01, and * indicates p < .05.

2.3.4. Magnitude model

The model investigating magnitude of coarticulation used F2 difference scores as its dependent variable. (The method for computing F2 difference scores is explained in § 2.2.5.2.) The results indicated that stress, direction, consonant, and time point each had a significant impact on the magnitude of coarticulation, with the effect of stress varying by vowel identity and direction. Vowel identity did not have a global impact on coarticulatory magnitude apart from stress. The particulars of these effects are discussed in detail in the following paragraphs.

In the magnitude model, the main effect of Stress was significant ($F(2, 2232.071) = 13.724$, $p < .001$), and pairwise comparisons between stress levels showed a significantly smaller magnitude of coarticulation in the Target Stressed condition ($M = 0.024$) than in either the Trigger Stressed ($M = 0.045$, $p < .001$) or Neither Stressed ($M = 0.037$, $p = .003$) conditions. Three two-way interactions involving Stress provide a more detailed look at what lies behind this result. The Stress by Trigger interaction ($F(2, 2220.190) = 21.577$, $p < .001$) and following post-hoc tests reveal that this pattern of greater coarticulation in the Trigger Stressed and Neither Stressed conditions was driven entirely by target /e/; target /o/ showed no significant differences across Stress conditions in pairwise comparisons. Similarly, the Stress by Consonant interaction ($F(2, 2218.581) = 8.299$, $p < .001$) and post-hoc tests pointed to /p/ as a driving force behind the main effect of Stress: the observed pattern of Target Stressed > Trigger, Neither Stressed appeared in pairwise comparisons for /p/, while /k/ demonstrated no significant differences across Stress conditions. Thus, in examining the impacts of Vowel and Consonant on the magnitude of coarticulation across Stress conditions, it emerges that differences across Stress conditions, with coarticulation favoring unstressed targets, appear only for Target /e/ (but not /o/) and intervening /p/ (but not /k/).

The related Stress by Direction interaction ($F(2, 2225.311) = 63.611$, $p < .001$) was due to differing patterns across directions: in the carryover direction, the Trigger Stressed condition exhibited significantly greater coarticulation ($M = 0.089$) than either the Target Stressed ($M = 0.036$, $p < .001$) or Neither Stressed ($M = 0.039$, $p < .001$) conditions, while in the anticipatory

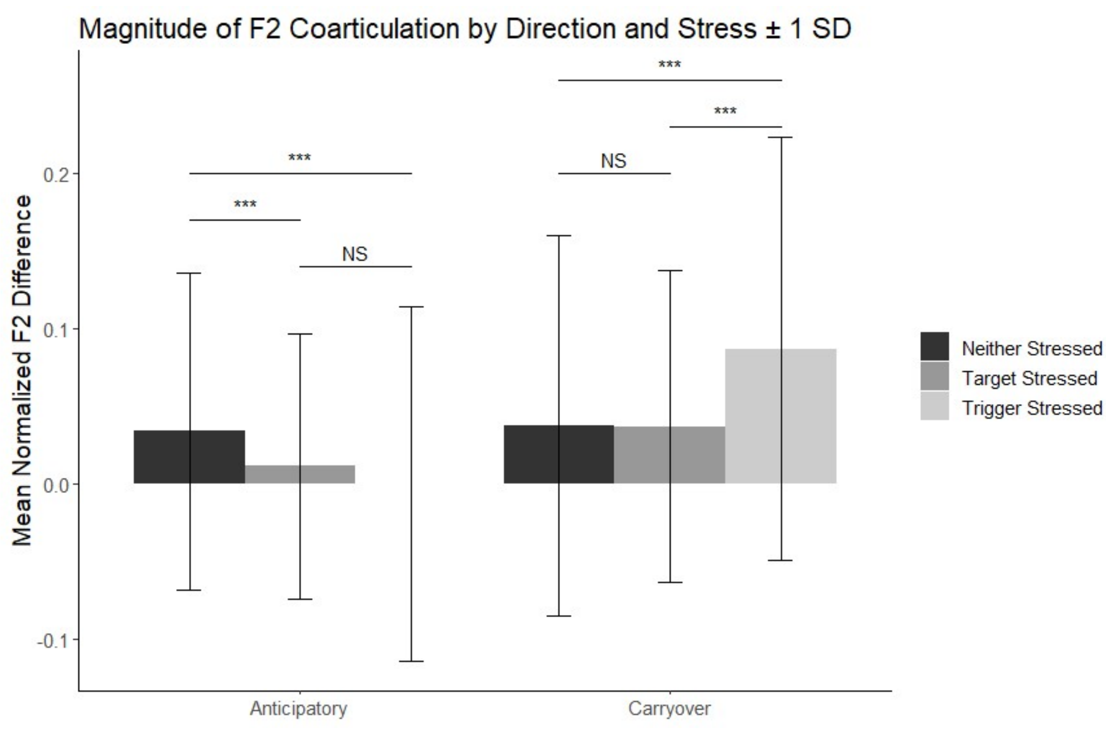

Figure 9: Magnitude of coarticulation in Spanish, given by mean F2 difference scores, across Direction and Stress conditions. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$.

direction, the Neither Stressed condition (M = 0.036) outweighed both of the others (M = 0.012, p < .001 for Target Stressed, M = 0.001, p < .001 for Trigger Stressed). (See Figure 9.) Thus, both directions favored unstressed targets, but the preferred unstressed condition (the one displaying the greatest coarticulation) varied by direction.

These results confirm Hypothesis 1, which posited that stressed vowels would make poorer targets of coarticulation than their unstressed counterparts. This effect is driven by words with Target /e/ and intervening consonant /p/; target /o/ and intervening /k/ did not accompany differences in magnitude of coarticulation by Stress. Limited support was found for Hypothesis 2, which predicted the greatest coarticulation in the Trigger Stressed condition, even above and beyond Neither Stressed. This pattern was present in the carryover direction, but not the anticipatory one.

The main effect of Direction was significant ($F(1, 2219.309) = 137.811$, $p < .001$), with greater coarticulation in the carryover direction (M = 0.054) than the anticipatory (M = 0.016). The significant interaction between Vowel and Direction ($F(1, 2219.537) = 5.199$, $p = .023$) revealed that this effect was more pronounced with Target /o/ than Target /e/, as shown in Figure 10; pairwise comparisons between the two directions within each target vowel showed a

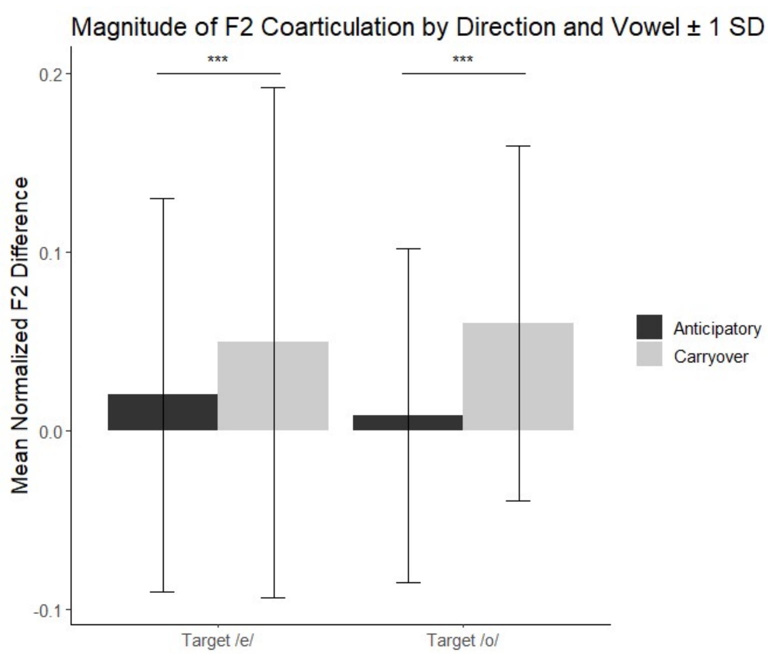

Figure 10: Magnitude of coarticulation in Spanish, given by mean F2 difference scores, across Direction and Vowel. Error bars display one standard deviation above and below the mean. *** indicates p < .001, ** indicates p < .01, and * indicates p < .05.

significant difference across directions for both vowels, with a greater difference for /o/. Thus, a strange asymmetry emerges: coarticulation in /e/ depends on stress, but coarticulation in /o/ depends on direction. This asymmetry is discussed further in § 2.4.3.

The effect of Vowel was not significant ($F(1, 2221.002) = 0.011$, $p = .917$), showing that magnitude of coarticulation did not differ significantly across target vowels. By contrast, the main effect of Consonant was significant ($F(1, 2218.354) = 319.216$, $p < .001$): /p/ permitted far greater VV coarticulation across it ($M = 0.064$) than /k/ did ($M = 0.007$). A second asymmetry appeared in the relationship between Vowel and Consonant ($F(1, 2219.503) = 1579.112$, $p < .001$). Intervening /k/ increased the magnitude of coarticulation for /o/ ($M = 0.071$) (but not /e/ ($M = -0.057$, $p < .001$)) and intervening /p/ increased coarticulation in /e/ ($M = 0.129$) (but not /o/ ($M = 0.000$, $p < .001$)). The two-way Vowel by Consonant interaction owed its significance to this affiliation, displayed visually in Figure 11.

Finally, the main effect of Time Point was also significant (F(1, 2217.353 = 81.804, $p < .001$), with greater coarticulation at vowel edge ($M = 0.05$) than at vowel midpoint ($M = 0.021$). Numerous significant two- and three-way interactions were included in the model, including

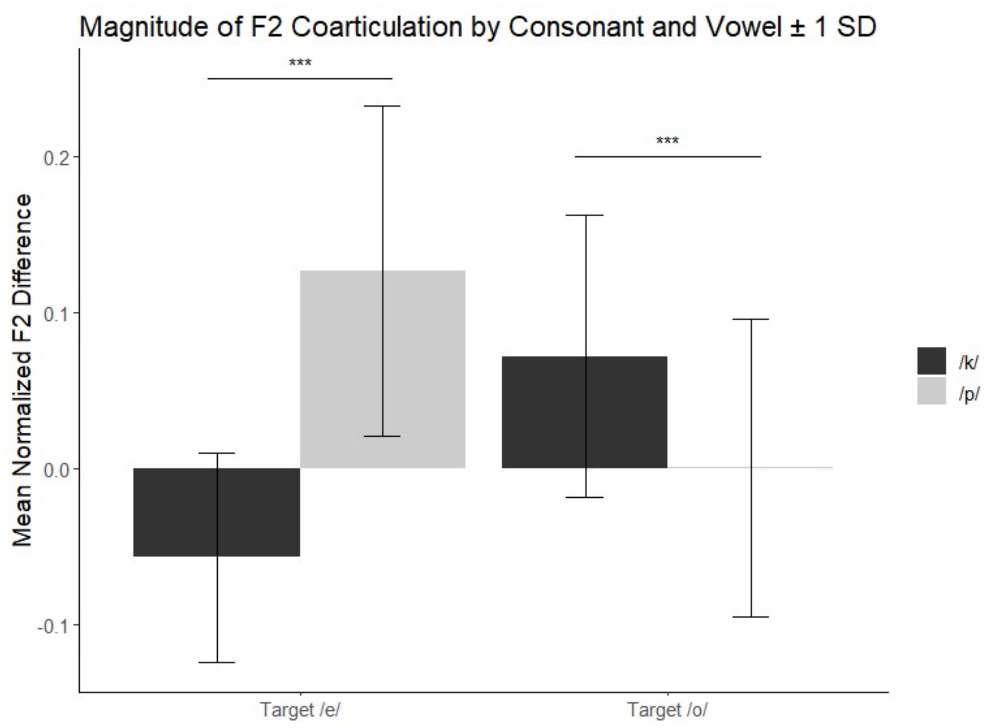

Figure 11: Magnitude of coarticulation in Spanish, given by mean F2 difference scores, across Consonant and Vowel. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$.

some not mentioned here; these results are reported in Appendix C. Thus, the main findings of the magnitude model were that (1) carryover coarticulation was greater than anticipatory; (2) the particular unstressed condition displaying the greatest coarticulation varied by direction; (3) unstressed vowels coarticulated more than stressed ones in words with target /e/ and intervening /k/; and (4) coarticulatory magnitude for /e/ depended on stress, while that of /o/ depended on direction.

2.3.5. Summary of results

The main effect of Trigger, indicating coarticulation, was significant for the carryover models at vowel edge and midpoint, but for the anticipatory models only at vowel edge. This corresponded to the results of the magnitude model, which indicated greater coarticulation in the carryover direction than the anticipatory. Furthermore, stress had a role to play in mediating coarticulation in each model, as shown in all five models by a significant three-way interaction between Stress, Target, and Trigger. In all models, the effect of stress on coarticulation varied by target vowel. The magnitude model reinforced this result, with the additional caveat that a decrease in magnitude of coarticulation for stressed targets appeared only with target /e/ and intervening /p/, while magnitude remained stable (and lower) across stress conditions for target /o/ and intervening /k/. Furthermore, coarticulation was greatest in the Trigger Stressed condition in the carryover direction, but in the Neither Stressed condition in the anticipatory direction. Thus, stressed vowels emerged as the worst targets of coarticulation as predicted, but, contrary to the hypothesis, they were only sometimes the most effective as triggers. A summary of results for the significance models and the magnitude model, divided by stress, is available in Table 5.

The magnitude model confirmed that the magnitude of carryover coarticulation was greater than that of anticipatory, that coarticulation was greater at vowel edge than at midpoint, and that neither target vowel underwent a greater magnitude of coarticulation than the other. It also highlighted two asymmetries: in the first, the magnitude of coarticulation exhibited by target /e/ (but not /o/) responded to changes in Stress, while target /o/ (but not /e/) responded to Direction. In the second, /k/ reinforced coarticulatory effects for /o/ and blocked them in /e/, while /p/ reinforced coarticulation in /e/ and blocked it for /o/.

Table 5: Post-hoc results of Stress by Target by Trigger interaction for four models in Spanish. *** indicates p < .001, ** indicates p < .01, and * indicates p < .05. NS denotes "not significant." Shaded cells are significant.

Target Vowel	Stress	Significance & Mean F2 Difference Scores			
		Anticipatory Edge	Anticipatory Midpoint	Carryover Edge	Carryover Midpoint
Target /e/	Target Stressed	* 0.035	NS -0.025	** 0.045	NS -0.017
	Trigger Stressed	* 0.047	NS -0.006	*** 0.098	*** 0.052
	Neither Stressed	NS 0.064	NS 0.005	*** 0.080	** 0.029
Target /o/	Target Stressed	NS 0.010	NS 0.027	* 0.055	NS 0.065
	Trigger Stressed	* -0.0278	NS -0.016	*** 0.119	* 0.079
	Neither Stressed	NS 0.027	NS 0.038	* 0.029	NS 0.007

In summary, four general trends emerged: (1) significant carryover coarticulation was widespread at vowel edge, persisting in some cases until vowel midpoint, while anticipatory coarticulation at vowel edge was found only in some stress conditions and did not persevere until vowel midpoint; (2) carryover coarticulation always had a greater magnitude than anticipatory; (3) stressed targets impeded coarticulation, while stressed initial syllables intensified it; and (4) /p/ impeded coarticulation with /o/ and intensified it for /e/, while /k/ enhanced coarticulation in /o/ and blocked it in /e/.

2.4. Discussion

2.4.1. Directional asymmetries in coarticulation

The experimental design was successful in triggering VV coarticulation, quantified as differences in normalized F2 between the canonical and coarticulated conditions. The two coarticulatory directions exhibited notably different behaviors: anticipatory coarticulation was of shorter duration and lesser magnitude, while carryover coarticulation persisted longer and was of a greater magnitude. The presence of coarticulation was confirmed in the statistical analysis through the main effect of Trigger, which provided a global indication of coarticulation for each direction and time point. Trigger was significant in the anticipatory direction at vowel edge, but not midpoint, and in the carryover direction at both vowel edge and vowel midpoint, suggesting that carryover coarticulation persisted further into the steady state of the vowel, since it remained statistically detectable at midpoint. The magnitude of coarticulation, evaluated in the magnitude model with F2 difference scores, was also statistically stronger in the carryover direction than the anticipatory across time points. Thus, one of the core findings of the study is that carryover coarticulatory effects are stronger and more stable than anticipatory ones in Spanish non-words. Furthermore, significant effects with a larger magnitude at vowel edge tended to remain significant at midpoint, pointing to a connection between magnitude and duration of coarticulation.

Past studies have shown that some languages habitually exhibit stronger VV coarticulatory effects in one direction than the other: English, for example, is widely found to exhibit primarily carryover VV coarticulation (Beddor et al., 2002; Bell-Berti & Harris, 1976; Manuel & Krakow, 1984), while anticipatory effects are stronger than carryover in Shona, Swahili, Tatar, and Turkish (Beddor et al., 2002; Beddor & Yavuz, 1995; Conklin, 2015; Manuel & Krakow, 1984). Neither direction of assimilation is yet established as strongly prevalent in Spanish when it comes to VV coarticulation. Recasens (1987) examined Spanish VV coarticulation between /i/ and /a/ across intervening /r, ɾ, β, l/ and reported no clear overarching preference for one direction of coarticulation over another. The only other study examining VV assimilation in Spanish of which I am aware, Henriksen (2017), analyzed only anticipatory assimilation. Thus, previous research provides no foundation for conclusions as to whether the preference for carryover VV effects in the current data is natural to Spanish.

One possible cause for the preponderance of carryover coarticulation over anticipatory is participants' knowledge of English as a second language and immersion in an English-language environment at the time of the study. The effect of bilingualism on VV coarticulation is a topic which has received little study, no doubt in part because establishing a VV coarticulation pattern specific to a given language is a daunting task, and without one it is impossible to assign coarticulatory patterns a first language (L1) or second language (L2) origin. Nevertheless, other aspects of first language phonetics and phonology, most often the realization of voicing via Voice Onset Time (VOT), have been shown to be affected by exposure to second language (Chang, 2012; Flege, 1987; Sancier & Fowler, 1997). Therefore, at least in theory, it is possible for VV coarticulation to be subject to influence from the L2 (in this case, English), leading to larger carryover effects.

A final factor that may have led to decreased anticipatory coarticulation in the present study was the exclusive use of non-words, which are both unfamiliar, at least to some degree unnatural, and lack a lexical entry. While these traits render non-words distinct from their real counterparts, it is not clear if or how they impact coarticulation in either direction. While anticipatory coarticulation entails an undeniable element of cognitive planning (Henke, 1966; Whalen, 1990), this cognitive component is not absent in non-words. Indeed, in the very study illustrating the role of articulatory planning in anticipatory coarticulation, Whalen (1990) was successful in measuring anticipatory coarticulation in nonsense strings produced by speakers of American English. Only when a delay in presentation of the second syllable impeded the speakers' ability to plan the utterance in full at the outset did anticipatory coarticulation subside. His finding demonstrates that anticipatory coarticulation is present in non-words even in English, a language which typically exhibits far stronger carryover effects than anticipatory ones. Thus, it does not seem likely that the use of non-words in the present study was a primary cause of the striking divide between substantial carryover and negligible anticipatory effects found in the Spanish data.

To summarize, the predominance of carryover over anticipatory VV coarticulation found in the present study could be a natural attribute of the Spanish language or a result of the influence of English as a second language. A less likely scenario is that the lack of a lexical entry associated with non-words led to a decrease in anticipatory effects. Further research is necessary to resolve this issue.

2.4.2. Effect of stress on VV coarticulation

A central goal of this study was to determine whether unstressed vowels were more likely to undergo VV coarticulation than stressed vowels. I predicted that stressed target vowels would undergo less coarticulation than unstressed targets, as has been found in numerous studies in many different languages (see, e.g., Beddor et al., 2002; Fowler, 1981; Majors, 2006; Mok, 2012; Nicolaidis, 1999; Recasens, 2015). Additionally, I hypothesized that stressed vowels may be more successful than unstressed ones in triggering coarticulation.

This prediction with respect to stressed targets held true in the majority of scenarios I examined. Stressed targets always exhibited the least amount of coarticulation or failed to demonstrate statistically significant coarticulation. The magnitude model reinforced this finding, showing that stressed targets exhibited a significantly smaller magnitude of coarticulation than their unstressed counterparts. Some asymmetry was present across directions in that anticipatory coarticulation in stressed /e/ was statistically significant, while the Neither Stressed condition of unstressed /e/ was not (albeit with a marginal *p*-value of .050). However, since the magnitude of coarticulation remained lower for anticipatory stressed /e/ than unstressed /e/, I do not attribute much weight to the difference in significance in the anticipatory model. Thus, the prediction that stressed vowels would undergo less VV coarticulation was largely confirmed, supporting Hypothesis 1.

I propose that stressed target vowels display a decreased propensity toward VV coarticulation because they are more likely than their unstressed counterparts to be hyperarticulated and thus articulatorily stable. Hyperarticulated segments may involve more pronounced articulatory gestures, longer closures, or tighter constrictions, and in the case of vowels, assume a closer relationship with the presumed vowel target (de Jong, 1995; de Jong et al., 1993). This dedication to canonical productions naturally discourages extreme VV coarticulation, either through the greater stability or the increased distance from the center of the vowel space.

The second core question of this study was whether stressed vowels make better or worse triggers of coarticulation. The same stress-related traits that render stressed vowels resistant to VV coarticulation may also serve to make them better coarticulatory triggers. The larger, more exaggerated gestures appearing in hyperarticulated segments require larger movements from the articulators and more specific and extreme final articulations (de Jong et al., 1993), leaving little allowance for coarticulation in stressed targets. These larger movements are performed at a cost to the articulation of surrounding segments: the greater displacement allows for a longer period of overlap with neighboring gestures, causing the stressed vowel to also trigger coarticulation with greater frequency. Thus, unstressed segments, which involve less exaggerated gestures, are expected to be less effective at triggering coarticulation. This issue has received little attention in earlier work, except insofar as studies of disyllables that showed less coarticulation on stressed syllables, by design, also demonstrated more coarticulation associated with stressed triggers (e.g., Beddor & Yavuz, 1995; Majors, 2006; Nicolaidis, 1999; Recasens, 1987). One study that specifically targeted this hypothesis is Cho (2004). Investigating prosodically accented instead of lexically stressed vowels, Cho (2004) tested the hypothesis that prosodically prominent syllables are more aggressive as triggers of coarticulation in English, but found only limited evidence supporting this hypothesis. My data, by contrast, provide partial support for the claim that stressed vowels are more effective at triggering VV coarticulation in unstressed targets than unstressed vowels are. The discrepancy between this finding and previous research may be attributable to language-specific factors or the disparity between the type of accent examined by each study (prosodic accent in monosyllabic target words versus word accent in multisyllabic target words).

My attempt to disambiguate the Target Stressed and Trigger Stressed conditions, often conflated in disyllabic designs, found that the greatest coarticulation occurred when stress fell on the initial syllable – that is, in the Trigger Stressed condition for carryover words and the Neither Stressed condition for anticipatory ones. This finding suggests that the question behind Hypothesis 2 may not be the most useful one to ask; whether the trigger is stressed may be secondary to the wider view of how target, trigger, stress, and direction align. Future studies wishing to investigate this question should consider including target vowels other than V_2 in order to separate the effects of stress and direction from that of target vowel location.

On a minor note, stress had a significant effect on F2 in general (as a main effect) despite the lack of qualitative vowel reduction in Spanish, showing that stress affects vowel phonetics even in the absence of phonologically categorical reduction. This result is in agreement with previous findings for Spanish (Romanelli, Menegotto, & Smyth, 2018).

In summary, the results of the current study with regard to stress indicate that stressed vowels coarticulate less often and to a lesser degree. This finding confirms the results of previous studies, prominently Recasens (2015), which investigated the effect of stress on VV coarticulation in Catalan and found that stressed vowels coarticulated less than their unstressed counterparts. Additionally, this study disambiguates the outcome of previous works that collapsed the effects of stressed targets and unstressed triggers, finding that stressed triggers induce greater coarticulation under at least some conditions.

2.4.3. Differences across target vowels

Another key asymmetry that emerged in the present data related to differences in behavior between targets /e/ and /o/; in particular, target /e/ exhibited significant coarticulation under a wider range of stress conditions (see Table 5) than target /o/. Target /o/, on the other hand, frequently coarticulated only under 'optimal' conditions – that is, when an unstressed target coarticulated with a stressed trigger. Thus, although the magnitude of coarticulation did not differ when both /e/ and /o/ coarticulated under the same stress conditions (no significant Trigger by Target interactions in the directional models and no main effect of Vowel in the magnitude model), the greater incidence of coarticulation in /e/ suggests it has a relatively greater propensity toward assimilation than other vowels.

Another acoustic asymmetry between /e/ and /o/ may be relevant here. In Spanish, /e/ demonstrates a higher degree of overall acoustic variability than /o/, as measured through F2 standard deviations. Bradlow's (1995) study of Spanish found a standard deviation of 131 Hertz for /e/, but only 99 Hz for /o/. My data support Bradlow's finding that /e/ is more acoustically variable than /o/. Canonical productions of /e/ in this study had a standard deviation of 302 Hz (0.124 normalized units), while canonical /o/ had a standard deviation of 104 Hz (0.099 normalized). The idea that low-density vowel inventories, which implicitly correspond to greater acceptable variability in vowel acoustics, consistently allow greater VV coarticulatory effects is widespread in previous research (Manuel, 1990), though also hotly disputed (Mok, 2012). The current data suggest that, within a single vowel inventory, greater acoustic variability may be predictive of increased susceptibility to coarticulation.

The magnitude model offers further insight into the vowel-specific coarticulatory behavior of /e/ and /o/: in particular, it highlights the affinity of /e/ to /p/ and /o/ to /k/. Each vowel exhibited a more forward position in the acoustic vowel space in /k/ context and a backer position in /p/ context, as shown in Figure 12, an effect which may have been amplified by the recurrence of a single consonant in each target word.

Velar consonants are typically characterized by an elliptical, rather than pendular, movement of the tongue body (Mooshammer, Hoole, & Kühnert, 1995), wherein the tongue body pushes up and forward during and following the velar closure. The distinctive movement of the tongue body should lead directly to a fronted articulation of the following vowel through CV coarticulation, and the additive acoustic effect of this CV coarticulation, compounded by VV coarticulation, differs for /e/ and /o/. When combined with /k/ and a triggering vowel /o/, F2 of /e/ should raise through CV coarticulation with /k/ and lower due to VV coarticulation with /o/; these opposing effects result in a net appearance of no coarticulation. For /o/, VV coarticulation with /e/ raises F2, compounding the effect of CV coarticulation with /k/. Thus, the apparently greater VV coarticulation of /ko/ and /pe/ syllables when compared to their /ke/ and /po/ counterparts reflects at least in part the combined impact of VV and CV coarticulation amplifying one another.

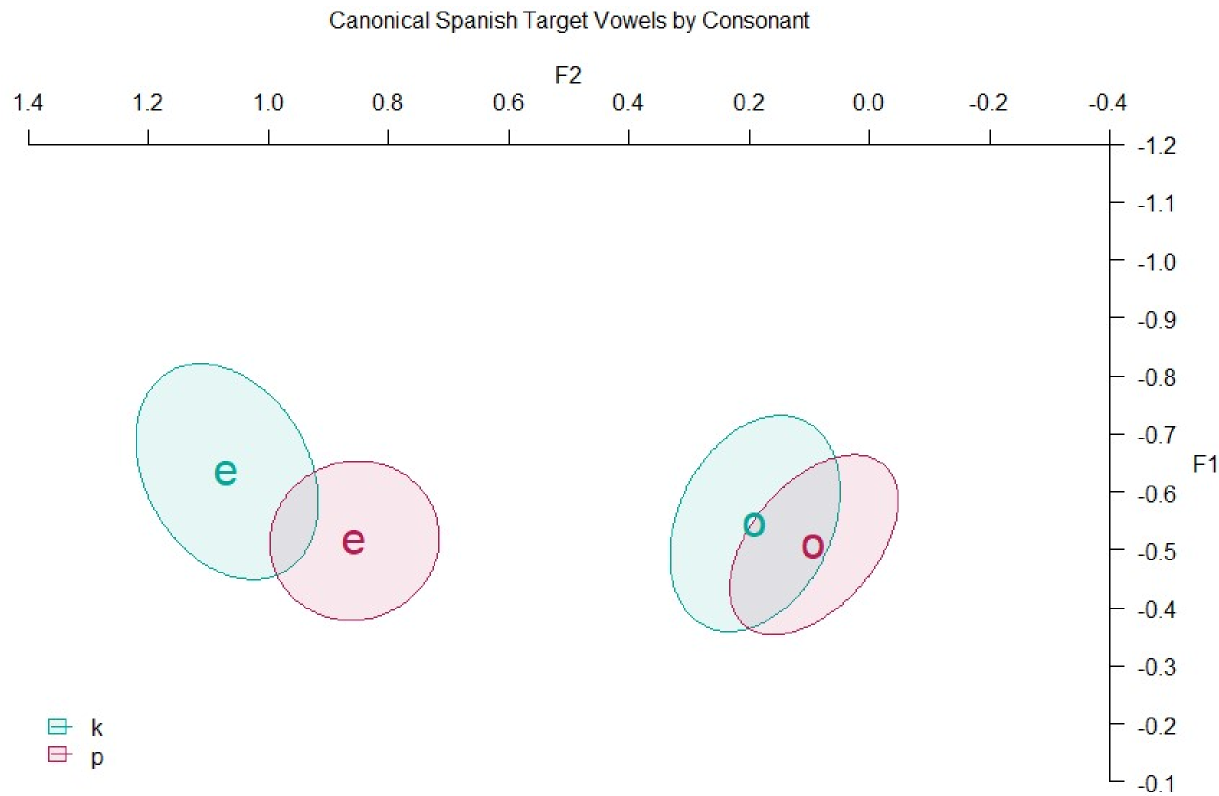

Figure 12: Canonical Spanish vowels by consonant with 68% confidence ellipses

2.4.4. Conclusion

The results of the present study demonstrate that VV coarticulation in Spanish is governed by a complex interaction among several factors; those examined most closely here are target vowel identity, stress, and consonant. The data show that, as expected, stressed vowels were less susceptible to VV coarticulation than unstressed ones. The question of whether stressed triggers are more effective at inducing coarticulation in unstressed targets than are unstressed triggers was partially supported, since the greatest coarticulation always appeared in one of the two unstressed conditions. Future work should disambiguate the Trigger Stressed and Neither Stressed conditions from syllable order and coarticulatory direction by measuring VV coarticulation in syllables other than V_2.

With regard to stress, the hierarchy of coarticulation frequency and magnitude as a function of stress that emerged in the present study is the following: in the anticipatory direction, unstressed triggers acting on unstressed targets exhibited greater coarticulation than stressed triggers paired with unstressed targets or unstressed triggers with stressed targets, and in the carryover direction, stressed triggers acting on unstressed targets demonstrated greater coarticulation than either unstressed triggers with stressed targets or unstressed triggers with unstressed targets. However, I also demonstrate that this hierarchy is not inviolable. Stressed targets can undergo coarticulation – under some circumstances to a degree comparable to that of unstressed targets.

With respect to the effect of vowel identity, the results suggest that the magnitude of VV F2 coarticulation in Spanish is relatively similar for /e/ and /o/, though /e/ was more susceptible to coarticulatory effects across stress conditions than /o/ was. Additionally, the magnitude of coarticulation increased for target /e/ in /p/ context and target /o/ in /k/ context, most likely due to the fact that CV coarticulation with the velar interacts with VV coarticulation, reinforcing the fronting of /o/ in the context of /e/ and counteracting the retracting of /e/ in the context of /o/. Finally, the data displayed coarticulation of greater magnitude and duration in the carryover than the anticipatory direction, though the origin of this asymmetry is yet to be determined.

3. TATAR

Portions of this chapter have been accepted for publication in the Proceedings of the 19th International Congress of Phonetic Sciences.

3.1. Introduction

Volga Tatar [ISO 639-3 code tat] is a member of the Kipchak branch of the Turkic language family spoken by 5 million speakers around the world (Comrie, 1997); its largest community is located in the Republic of Tatarstan in Russia (Sahan, 2002). Like many Turkic languages, Tatar is known for its vowel harmony: backness harmony in Tatar is well-attested and affects all the vowels of the language, while rounding harmony is restricted to mid vowels and has a disputed status (see Comrie, 1997; Johanson & Csató, 1998; Poppe, 1968 for varying accounts of Tatar rounding harmony). Work on Tatar phonology typically focuses on vowel harmony, but despite this focus on vocalic processes, no formal acoustic description of the Tatar vowel system is available. Because of this, the purpose of this chapter is twofold: to provide an acoustic description of Tatar vowel phonemes across a wide cross-section of speakers and to present an account of vowel-to-vowel coarticulation in Tatar, with the intent of increasing understanding of the synchronic relationship between vowel harmony and vowel-to-vowel coarticulation.

Table 6: Vowels of Tatar (* marks disputed status)

	[-back]		[+back]	
	[-rnd]	[+rnd]	[-rnd]	[+rnd]
[+hi][-lo]	/i/	/ʉ/	/ɨ/*	/u/
[-hi][-lo]	/e/	/ø/	/ə/	/o/
[-hi][+lo]	/æ/		/ɑ/	

Previous descriptions of the Tatar vowel inventory do not agree on how many vowel phonemes exist in Tatar; some report nine (Poppe, 1968; Sahan, 2002) and some ten (Comrie, 1997) (see Table 6). This discrepancy arises due to differing treatment of the vowel /ɨ/, which is analyzed either as a VC sequence /əj/ (Berta, 1998) or as a single, frequently diphthongized, phoneme /ɨ/ (Comrie, 1997). The argument for the phonemic status of /ɨ/ rests on parallel diphthongization of the high vowel /i/, as well as established harmonic alternations between /i/ and /ɨ/ (Comrie, 1997). I argue for the independent phonemic status of /ɨ/ on phonological and acoustic grounds.

While the Tatar vowel system is phonologically symmetrical, exhibiting a satisfying balance between front and back vowels, the phonetic distribution of Tatar vowels is not so even. The four mid vowels and /ʉ/ are highly centralized (Comrie, 1997; Poppe, 1968); mid vowel centralization hearkens back to the Volga vowel shift, a historical change that reversed the high and mid vowels in Volga Turkic languages (Berta, 1989). (See § 3.1.3.) Because of this, the acoustic analysis is expected to reveal a high degree of crowding in the center of the vowel space.

This chapter will also examine allophonic alternations for /ɨ/ and /ɑ/. It is widely recognized that the phoneme /ɑ/ has two allophones, a rounded allophone [ɒ] surfacing in initial syllables and an unrounded allophone [ɑ] in non-initial syllables (Berta, 1998; Comrie, 1997; Poppe, 1968), while /ɨ/ undergoes diphthongization in stressed syllables (Comrie, 1997). This chapter will verify acoustically what previous work has established impressionistically, recording the acoustic qualities of these phonemes and allophones and exploring the influence of stress on Tatar vowel production.

3.1.1. Tatar vowel harmony

Backness harmony is widespread and well-described in Tatar, while rounding harmony is disputed. In backness harmony, the vocalic system is divided evenly into two classes of five, such that allomorphs with front vowels surface when the stem is front and back allomorphs appear with back vowel stems. This process is most consistent in lexemes of Turkic origin and older loans from Arabic or Farsi, although many disharmonic roots exist among loanwords. In Arabic and Farsi loan words, disharmonic roots containing /ɑ/ and /i/ are common and affix assignment with regard to harmony does not follow a fixed pattern. (Neither /ɑ/ nor /i/ consistently behaves in an opaque or transparent fashion in Tatar, blocking the progress of harmony or remaining invisible to it.) Recent loans, particularly from Russian, introduce additional vowels and frequently disobey harmony; due to high levels of bilingualism, Russian loans generally exhibit Russian phonology (Comrie, 1997). The set of target words for this study specifically avoids Russian loan words. Furthermore, previous descriptions of Tatar agree that

Tatar mid vowel sequences led by /o/ or /ø/ show unusual behavior; conflicting accounts ascribe this to rounding harmony (Johanson & Csató, 1998), phonotactics (Poppe, 1968), and gradient assimilation (Comrie, 1997). To avoid any confusion, this work only examines initial /o/ and /ø/ and instances of /e/ and /ə/ not preceded by /o/ or /ø/.

3.1.2. Stress in Turkic and in Tatar

Historically, Turkic languages have exhibited two types of word-level prominence – specifically, a pitch accent that fell on the final accentable syllable of each word, excluding clitics and a small handful of affixes that behave like clitics, and a stress accent, which was characterized by greater intensity and fell on the initial syllable of the word (Johanson, 1998b; Menges, 1968). The division between pitch accent and stress accent is used to explain the historical development of vowel harmony in Turkic: the left-to-right spreading of harmony was driven by the stability of the initial stressed vowel, to which the following vowels assimilate. After vowel harmony was phonologized, the stress accent shifted to the final syllable, where it reinforces the final pitch accent (Chen, 2005; Menges, 1995).

While currently available descriptions of Tatar do not assert the existence of any form of pitch accent or distinguish between the two historically differing types of accent, they do provide summaries of the location of prominence in Tatar. In these descriptions, stress falls on the final syllable of the word, with key exceptions governed by syntax and morphology (Berta, 1998; Comrie, 1997; Poppe, 1968; Sahan, 2002). Loan words from Russian tend to keep the stress pattern of their original language (Comrie, 1997; Poppe, 1968). This study is not intended to investigate the nature of word-level prominence in Tatar and was not designed to distinguish between pitch accent and stress accent, if any such distinction indeed exists; target word selection is restricted to words with prominence on the final syllable, as is most common in Tatar. However, a thorough analysis of the effect of pitch accent on coarticulation compared to hyperarticulated stress may make an excellent subject of future study, as the two prominence systems likely exert notably differing influences on vowel articulation and acoustics.

3.1.3. Volga Vowel Shift

Languages of the Volga region, including Tatar, display key differences from related Turkic languages with regard to their vowel inventories due to a historical process known as the

Volga Vowel Shift. Through the Volga Vowel Shift, vowels that were once high were reduced, centralized, and lowered, while the mid vowels were raised to fill the vacant positions in the upper part of the vowel space (Johanson, 1998a; Sahan, 2002). This exchange accounts for the reduced, centralized nature of the Tatar mid vowel series /e, ø, ə, o/, as well as the systematic relationship between high and mid vowels in Tatar and other Turkic languages. (Consider the Tatar-Turkish cognates /bɛn/ ~ /min/ "I", /gœl/ ~ /gʉl/ "to smile", /dyrt/ ~ /dørt/ "four", and /kol/ ~ /qul/ "arm." Data is drawn in part from Sahan, 2002, p. 21.) This vowel shift also explains why rounding assimilation (or, as some analyses have posited, phonotactic restrictions related to round vowels) affect the mid vowels in Tatar, while rounding harmony targets high vowels in Turkish (for more on Turkish rounding harmony, see Clements & Sezer, 1982).

3.2. Tatar vowel space

This chapter contains two distinct studies of Tatar vowel acoustics: this section, § 3.2, presents a descriptive acoustic investigation of the Tatar vowel space, and the second half of the chapter, § 3.3, contains a study of VV coarticulation in Tatar. Each section is structured independently, with its own methods, results, and discussion.

3.2.1. Methods

3.2.1.1. Participants

Thirty-nine native speakers of Tatar completed a sentence reading task recorded with a Lavalier AT831b lapel-mounted cardioid condenser microphone and a Marantz PMD661MKII solid state recorder in a quiet room in Kazan, Russia. Due to recording quality issues, eleven recordings were deemed of insufficient quality for formant analysis, and one additional recording was discarded due to lack of fluency. The remaining 27 recordings were contributed by participants aged 18 – 68; 26 were female and one was male. All reported Tatar as their first language and were bilingual in Russian; additionally, some participants had studied third languages, including English, German, Turkish, Arabic, Farsi, French, Spanish, Italian, Esperanto, and Old Tatar. No participant had resided outside Russia for longer than 3 months or in regions of Russia where Tatar is not spoken for longer than one year.

3.2.1.2. Stimuli

For the vowel space analysis, thirty two- and three-syllable Tatar words provided samples of each vowel phoneme in a variety of consonantal contexts; these are displayed in Table 7. Due to phonotactic restrictions, stressed /o/ and /ø/ were not included; unstressed /e/ was also excluded. In the four lexical items containing strings of mid vowels beginning with a mid rounded vowel, only the initial rounded vowel was analyzed as a prototypical exemplar of its

Table 7: Target words for Tatar vowel space analysis. Rows marked in gray were also analyzed in the accompanying study of Tatar coarticulation.

Cyrillic	IPA	Gloss
Сафа	/sɒfɑ/	a proper name
нәфис	/næfis/	‘elegant, refined; artistic’
мәгърифәт	/mæʁrifæt/	‘education’
сәхифә	/sæxifæ/	‘page in history’
сәфәр	/sæfær/	‘second lunar month; voyage’
ара	/ɒrɑ/	‘interval’
шәрә	/ʃæræ/	‘nude’
зирәк	/ziræk/	‘shrewd, bright, smart’
пәри	/pæri/	‘fairy’
фәлсәфә	/fælsæfæ/	‘philosophy’
әфәнде	/æfænde/	‘gentleman’
урам	/urɑm/	‘street’
укыту	/uqətu/	‘teaching’
урман	/urmɑn/	‘forest’
корылык	/qorələq/	‘drought’
борыч	/borəɕ/	‘pepper, vegetable’
колак	/qolɑq/	‘ear’
өрек	/ørek/	‘dried apricot’
мөгез	/møgez/	‘horn’
абый	/ɒbɨj/	‘brother, uncle’
сыйфат	/sɨjfɑt/	‘quality’
кыйбат	/qɨjbɑt/	‘expensive’
үрмәкүч	/ʉrmækʉɕ/	‘spider’
күрше	/kʉrʃe/	‘neighbor’
бүлек	/bʉlek/	‘chapter’
ипи	/ipi/	‘bread’
сишәмбе	/siʃæmbe/	‘Tuesday’
кисәк	/kisæk/	‘piece, bit’
сәке	/sæke/	‘plank bed’
акыл	/ɒqɨl/	‘mind’

class. All stimuli exhibit stress on the final syllable in accordance with the most common pattern in Tatar phonology. Target words for the vowel space analysis were interspersed with those from the coarticulation study (described in § 3.3.2.2). Thus, each participant read a total of one hundred twenty sentences, each containing a target word analyzed either for the study of the Tatar vowel space or the coarticulation study. Because of the variety of stimuli recorded together, no additional filler items were introduced.

3.2.1.3. Procedure

Participants filled out a language background questionnaire and completed a sentence reading task. Target items and carrier phrases were separated into three blocks, randomized, and presented using E-Prime 2.0 (Schneider et al., 2002) in black font on a white screen. In four recording sessions, the E-Prime software experienced technical difficulties; these four participants completed the experiment through Praat's Experiment MFC (Boersma & Weenink, 2017), in which target sentences appeared in dark red font against a yellow background. After each block, participants had the opportunity to take a short break to prevent fatigue effects. All participants were compensated for their time.

3.2.1.4. Measurements

Recordings were digitized at 44.1 kHz and target vowels were segmented by hand in Praat v. 6.0.23 (Boersma & Weenink, 2017). The first two formants were extracted using Praat's Burg LPC algorithm at 10%, 50%, and 90% of the vowel; values were checked visually by a researcher and corrected by hand where necessary. In the vowel space analysis, additional formant measurements of oft-diphthongized /ɨ/ were taken at 20% and 80% of vowel duration. To reduce interspeaker variation, formant values were normalized using log-additive regression normalization, a procedure suitable for missing and unbalanced data (Barreda & Nearey, 2017) carried out in R v. 3.4.3 (R Core Team, 2017).

3.2.1.5. Analysis

For the acoustic description of the Tatar vowel space, means of normalized formant values at vowel midpoint were computed, and two linear mixed models were used to determine the degree of difference between vowels using SPSS v. 24.0.0.0 (IBM Corp, 2016). These models took Normalized F1 and Normalized F2 as their dependent factor, Subject as a random factor, and Vowel (ten levels), Stress (Stressed versus Unstressed), and Vowel by Stress as independent factors.

3.2.2. Results

3.2.2.1. Formant values by phoneme

Figure 13 displays the Tatar vowel space occupied by its ten phonemes (shown with 68% confidence ellipses) (McCloy, 2016). Table 8 displays average formant values (in Hz) at midpoint for each vowel, with separate values for the stressed and unstressed variants.

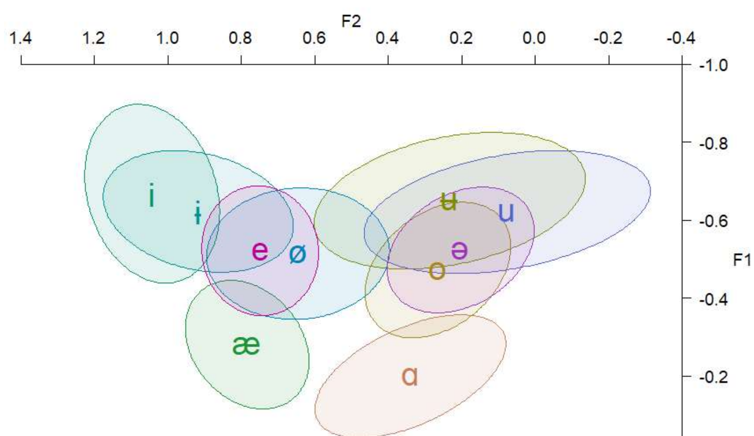

Figure 13: Tatar vowels (/ɨ/ restricted to unstressed utterances to exclude diphthongized variant)

Table 8: Tatar F1 & F2 means at vowel midpoint in stressed and unstressed syllables by vowel

Phoneme	Stressed		Unstressed	
	F1 (Hz)	F2 (Hz)	F1 (Hz)	F2 (Hz)
/i/	476.25	2584.40	462.94	2565.53
/e/	539.11	1916.83	--	--
/æ/	672.52	1977.73	691.54	1990.17
/ʉ/	494.47	1489.13	469.46	1077.76
/ø/	--	--	543.33	1742.22
/ə/	545.91	1027.03	533.57	1208.62
/ɑ/	771.97	1392.64	696.87	1110.46
/o/	--	--	567.28	1187.13
/u/	508.13	1345.96	482.39	878.85
/ɨ/	515.88	1927.55	487.21	2285.63

3.2.2.2. Results of LMMs differentiating vowel phonemes

Two linear mixed models with dependent variables of normalized F1 and F2 were used to confirm the efficacy of F1 and F2 in distinguishing the ten vowels under analysis across stress positions. A random factor of Subject, fixed factors of Vowel (ten levels) and Stress (stressed versus unstressed), and a Vowel by Stress interaction were included in each model. The factor Vowel was significant in both models (F1 model: $F(9, 4410.411) = 1188.224$, $p < .001$; F2 model: $F(9, 4410.795) = 2093.162$, $p < .001$); Table 9 presents the pairwise comparisons between vowels (with Bonferroni correction). Across the models, nine vowel pairs (out of 45) failed to differ significantly with regard to either F1 or F2; all vowel pairs were significantly different in at least in one dimension (F1 or F2).

Table 9: Pairwise comparison of factor Vowel with Bonferroni correction for Tatar vowel space analysis. *** indicates $p < .001$, ** $p < .01$, and * $p < .05$. "NS" indicates not significant. Cells right of the grey diagonal correspond to F2; those left of the grey cells, F1.

	/i/	/e/	/æ/	/ʉ/	/ø/	/ə/	/ɑ/	/o/	/u/	/ɨ/
/i/		***	***	***	***	***	***	***	***	***
/e/	***		**	***	***	***	***	***	***	***
/æ/	***	***		***	***	***	***	***	***	***
/ʉ/	NS	***	***		***	***	NS	*	***	***
/ø/	***	NS	***	***		***	***	***	***	***
/ə/	***	NS	***	***	NS		***	**	NS	***
/ɑ/	***	***	***	***	***	***		**	***	***
/o/	***	***	***	***	*	***	***		***	***
/u/	***	***	***	NS	***	***	***	***		***
/ɨ/	***	***	***	**	***	***	***	***	NS	

3.2.2.3. Stress and Stress by Vowel in LMMs differentiating vowel phonemes

The main effect of Stress was significant in both models (F1: $F(1, 4410.167) = 69.039$, $p < .001$; F2: $F(1, 4410.351) = 226.731$, $p < .001$), as was the Stress by Vowel interaction (F1: $F(6, 4410.288) = 28.356$, $p < .001$; F2: $F(6, 4410.573) = 212.908$, $p < .001$). Pairwise comparisons of the interaction with Bonferroni correction indicated a significant effect of stress on each vowel for either F1 or for F2, as summarized in

Table 10.

The direction of these effects is illustrated in Figure 14, which displays the F1 x F2 space for stressed and unstressed vowels (excluding /ɨ/, which is discussed in § 3.2.2.4 and § 3.2.3.1,

Table 10: Significance (value of *p*) for pairwise comparisons for Stress by Vowel interaction in Tatar

	F1	F2		F1	F2
/i/	< .01	NS	/ɨ/	< .001	< .001
/e/	--	--	/ə/	NS	< .001
/æ/	< .001	NS	/ɑ/	< .001	< .001
/ʉ/	< .01	< .001	/u/	< .01	< .001
/ø/	--	--	/o/	--	--

and /o/, /ø/, and /e/, for which both stressed and unstressed measurements were not available). Striking changes to the position and variability of several phonemes emerge under stress. The high round vowels /ʉ/ and /u/, in particular, exhibit far greater variability when stressed, while the front vowel /æ/ exhibits greater variability when unstressed. F2 of /ə/ falls when stressed, pushing this variant toward the periphery of the vowel space, while /ɑ/ shifts down and forward under stress. For /ɑ/, the stressed/unstressed division corresponds to the distribution of its rounded and unrounded allophones, with stress falling on the non-initial, unrounded allophone (in the stimuli used here).

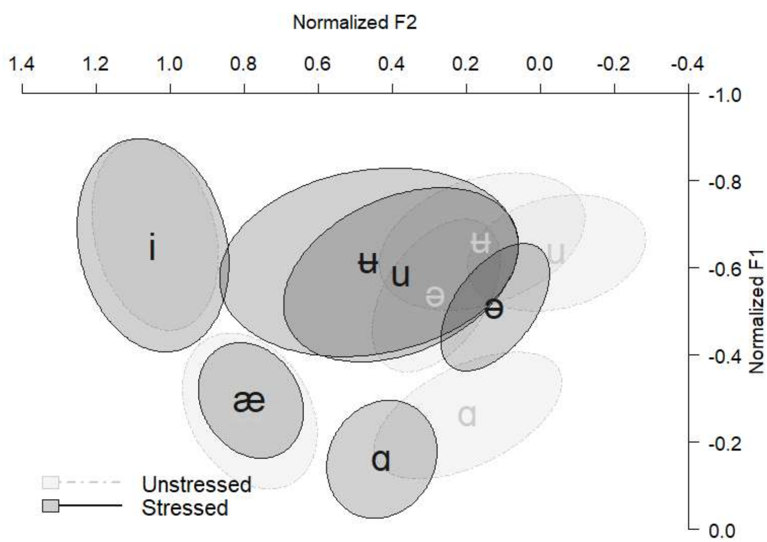

Figure 14: Stressed and unstressed Tatar vowels in F2 x F1 space with 68% confidence ellipses

3.2.2.4. High back unrounded vowel

Stress triggers a marked change in the behavior of the phoneme /ɨ/, which diphthongizes under stress. This change is reflected acoustically through F2 movement, as shown in Figure 15. F2 of stressed [ɨj] begins low, rises by vowel midpoint, and remains high until offset. By contrast, unstressed [ɨ] has a relatively steady F2, arcing neatly from onset to offset with the highest F2 at midpoint, as is typical for monophthongs. Stressed [ɨj] also has a greater duration (M = 99.70 ms; SD = 34.061) than unstressed [ɨ] (M = 66.45 ms; SD = 21.106), which may have reinforced its propensity to diphthongize.

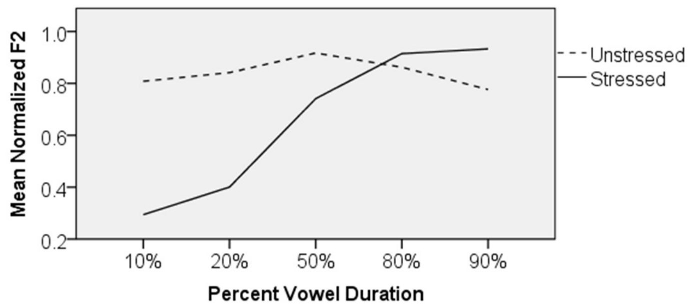

Figure 15: F2 values of Tatar /ɨ/ across five time points in the stressed and unstressed conditions

3.2.2.5. Repulsive force

To confirm the visual impression of central vowel space crowding given in Figure 13, the degree of repulsive force between vowels was calculated using the phonR package (McCloy, 2016) in R (R Core Team, 2017). Repulsive force is a representation of the degree of dispersion among vowel phonemes, and it is calculated using the inverse squared sum of the Euclidean distance between each vowel (Liljencrants & Lindblom, 1972; Wright, 2004). Higher values of

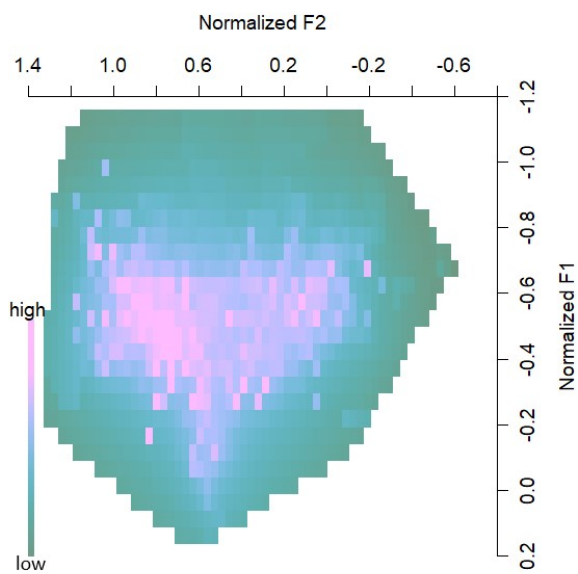

Figure 16: Heatmap of Tatar vowel space

repulsive force indicate greater overlap between phonemes (McCloy, Wright, & Souza, 2014). Figure 16 shows a heatmap displaying the degree of repulsive force at each F2 x F1 point in the Tatar vowel space. In Figure 16, the greatest crowding appears just forward of the center of the vowel space, particularly in the high-mid range, and central crowding is not as pronounced as in the F2 x F1 plot. This confirms a linguistic property long observed in impressionistic descriptions of the Tatar vowel space – namely, the widespread centralization found in many Tatar vowel phonemes.

3.2.3. Discussion

The phonological structure of the Tatar vowel system is symmetrical, with ten vowels evenly distributed across three levels of height, two of backness, and two of rounding. Phonetically, several Tatar vowels congregate in the central vowel space; the centralized mid vowels, alongside /ʉ/ and /ɨ/, contribute to overlap and greater repulsive force just inside the periphery. This central vowel space crowding contradicts an established typological trend for vowels to be evenly dispersed in the vowel space or concentrated in the periphery (Schwartz, Boë, Vallée, & Abry, 1997), rendering Tatar cross-linguistically unusual with regard to its vowel inventory. This rare trait is due in part to the Volga vowel shift, which reduced, centralized, and lowered once-high vowels to modern /e, ə, o, ø/ and raised historically mid vowels to /i, ɨ, u, ʉ/. The resultant centralization may owe its preservation in part to vowel harmony, which weakens the need for a clear distinction in backness, since the value of [back] for an entire word can be inferred from the initial vowel. If this is true, we may expect to find similarly weak F2 distinctions in other harmonizing languages, including those without a historical centralization process. Washington (2017) documents notable formant overlap across phonemes in three such languages, Turkish, Kyrgyz, and, to some degree, Kazakh, lending merit to the idea that backness harmony weakens the need for F2 to serve as a strong cue of vowel backness.

3.2.3.1. The phonological status of /ɨ/

One major disagreement in earlier work on the Tatar vowel system relates to the number of phonemes, specifically whether the high back unrounded vowel /ɨ/ consists underlyingly of one phoneme or two. Standard Tatar orthography reinforces the perception of /ɨ/ as a two-phoneme sequence by representing it with two graphemes, biasing native speaker intuitions on the question. Because of this, acoustic and phonological evidence provide more reliable arguments for phonemicity, and both plead in favor of /ɨ/ as a phoneme. Acoustic analysis shows that diphthongization of /ɨ/ occurs only in stressed environments; when unstressed, /ɨ/ is monophthongal. Furthermore, mean F2 of unstressed, monophthongal /ɨ/ differs significantly from that of unstressed /ə/, the phoneme proposed by Berta (1998) to fill the place of /ɨ/ in the nine-phoneme inventory (1088 Hz difference in F2, $p < .001$ in pairwise comparisons of Vowel by Stress). Thus, acoustic evidence argues for inclusion of /ɨ/ as a distinct phoneme. Phonological evidence strengthens this argument. In the negative suffix -/mI/, /ɨ/ alternates with /i/ with regard to harmony, suggesting that these vowels occupy parallel positions in the phonology.

3.2.3.2. The impact of stress on the Tatar vowel space

Stress affects Tatar vowel articulation profoundly, causing /ɨ/ to diphthongize and /y/, /u/, /ɑ/, and /i/ to shift their position within the F2 x F1 space. But by far the most dramatic change accompanying stress is the increase in F2 variability exhibited by stressed (but not unstressed) /u/ and /ʉ/. This may be due to vowel harmony: since the value of the feature [back] is specified for the word in the first syllable, and since stressed vowels are always word-final, the value of [back] and therefore the distinction between /u/ and /ʉ/ can be inferred from the first syllable of the word. Thus, in multisyllabic words, greater variability in the final syllable does not automatically result in a loss of intelligibility.

3.2.3.3. Allophones of /a/

Previous impressionistic accounts have proposed that Tatar /ɑ/ alternates between an initial round allophone [ɒ] and unrounded, noninitial [ɑ], corresponding in the present stimuli to stressed [ɑ] and unstressed [ɒ]. (This division typifies the standard variety of Tatar; degree of rounding in /ɑ/ is also a dialectal marker that undergoes significant geographic variation (Sattarova, 2014).) The present data confirm this assessment by demonstrating that /ɑ/ is higher and more retracted in the acoustic vowel space when unstressed, as visible in Figure 14, an acoustic change compatible with the effect of lip rounding.

3.2.4. Summary

This section reports the first large-scale spectrographic description of Tatar vowels and documents two typologically unusual traits: crowding of the central vowel space and dramatically increased F2 variability among stressed high round vowels. Both are potentially explainable by vowel harmony, which pre-specifies the backness of all noninitial vowels. This theory is supported by data from other harmonizing languages displaying a weak F2 backness distinction (Washington, 2017).

3.3. VV Coarticulation

3.3.1. Hypotheses

Previous studies have found contradicting results regarding the directionality of coarticulation in harmonizing languages: Beddor & Yavuz (1995) found primarily anticipatory coarticulation in Turkish, a language with left-to-right harmony, while Dye (2015) found that the primary direction of coarticulation in Wolof and Pulaar parallels that of harmony. Stress is also thought to play a role in determining coarticulatory directionality; many studies have found that coarticulation affects stressed vowels less than unstressed ones, resulting in a prevailing coarticulatory direction leading away from the stressed vowel (Beddor et al., 2002, Fowler, 1981, Magen, 1984, Majors, 2006, and Magen, 1997 on English; Mok, 2012 on Mandarin and Cantonese; Farnetani, 1990 on Italian; Nicolaidis, 1999 on Greek; Recasens, 2015 on Catalan). However, in harmonizing languages, stress is not reliably predictive of coarticulatory direction. In Beddor & Yavuz's (1995) investigation of Turkish, coarticulation is primarily right-to-left, moving away from the final stressed vowel, but in Dye's (2015) investigation, coarticulation is chiefly right-to-left in Pulaar and left-to-right in Wolof, despite both languages sharing word-initial stress that would be expected to generate left-to-right coarticulation. Thus, previous work does not reveal a clear synchronic relationship between stress, vowel harmony, and coarticulation. In this chapter, I test two contrasting hypotheses relating to coarticulatory direction.

Hypothesis 3: If maintaining a directional parallel between vowel harmony and coarticulation is a controlling factor in determining coarticulatory direction, carryover coarticulation is expected to outweigh anticipatory coarticulation in Tatar in order to match the left-to-right direction of harmony.

Hypothesis 4: If stress is the strongest predictor of coarticulatory direction, anticipatory coarticulation is expected to outweigh carryover in Tatar in order to preserve word-final stressed vowels as the best triggers and poorest targets of coarticulation.

3.3.2. Methods

3.3.2.1. Participants, procedure, and measurements

The participants, recording procedure, normalization, and formant measurements for the coarticulation study were identical to those described in § 3.2.1 for the Tatar vowel space analysis.

3.3.2.2. Stimuli

For the coarticulation analysis, participants read an additional ten target items containing disharmonic strings of vowels; these are given in Table 11. (Entries duplicated across Table 7 and Table 11, marked in gray, were used as control items in the coarticulation analysis or are harmonic words with vowels of different heights used to analyze coarticulation in height.)

Table 11: Stimuli used in Tatar coarticulation analysis. Items marked in gray were also analyzed in the accompanying study of the Tatar vowel space.

Cyrillic	IPA	Gloss
Сафа	/sɒfɑ/	a proper name
нәфис	/næfis/	‘elegant, refined; artistic’
сәфәр	/sæfær/	‘second lunar month; voyage’
ара	/ɒrɑ/	‘interval’
шәрә	/ʃæræ/	‘nude’
зирәк	/ziræk/	‘shrewd, bright, smart’
пәри	/pæri/	‘fairy’
афәт	/ɒfæt/	‘trouble, disaster’
гарәп	/gɒræp/	‘Arabic, Arab’
гафил	/gɒfil/	‘careless’
тарих	/tɒrix/	‘history’
җәфа	/ʑæfɑ/	‘torment, suffering’
шәраб	/ʃærɑb/	‘wine’
жираф	/ʑirɑf/	‘giraffe’
зифа	/zifɑ/	‘shapely, harmonious’

3.3.2.3. Analysis

Four linear mixed models were used to detect vowel-to-vowel coarticulation in height and backness in Tatar; backness coarticulation was analyzed as the dimension most closely paralleling harmony, while height coarticulation was included in order to discover if behaviors observed in backness were limited to this dimension or if the effect of harmony on coarticulation transcended dimension. Two models used F1 as a dependent variable to approximate vowel height, and two used F2 as a proxy for combined differences of backness and rounding. (For each formant, two models were run – one on measurements taken at the vowel edge closest to the trigger, 90% for first-syllable vowels and 10% for second-syllable vowels, and one on midpoint measurements.) In each model, Subject was included as a random factor; Item was not included, as models with both Subject and Item did not converge. Four independent variables, Consonant (/f/ versus /r/), Direction (Anticipatory versus Carryover), Target (/ɑ/ versus /æ/), and Trigger (/ɑ/ versus /æ/ versus /i/), were included in each model. Finally, four interactions were included: a Target by Trigger interaction, two three-way interactions between Consonant, Target, and Trigger and between Direction, Target, and Trigger, and finally the four-way interaction between Consonant, Direction, Target, and Trigger. Pairwise comparisons of Trigger with Bonferroni correction were carried out for each interaction with Trigger as well as its main effect, which had three levels. These models detected coarticulation by evaluating the significance of the difference in Trigger between the canonical and coarticulated conditions – for example, by comparing the coarticulated /a/ of /ʑæfɑ/ to the canonical /ɑ/ of /sɒfɑ/ to evaluate the carryover impact of /æ/ on /ɑ/.

In addition to the four models that used F1 and F2 as their dependent variable, two models evaluated the magnitude of coarticulation in various conditions by taking difference scores as their dependent variable. For each subject and target vowel, the mean F1 and F2 for vowels in canonical target words were calculated. This canonical mean was used as a baseline against which F1 and F2 difference scores were calculated for each vowel utterance: for each target vowel, the normalized F1 and F2 values were subtracted from the canonical mean for that vowel and participant. Finally, difference scores were assigned a sign such that positive values corresponded to coarticulation and negative values to dissimilation, under the assumption that F1 was lowest for /i/, followed by /æ/ and then /ɑ/, while F2 was lowest for /ɑ/, followed by /æ/ and then /i/. These models were fit to the data to achieve the best possible fit, using Target Vowel (/ɑ/ versus /æ/), Trigger Vowel (/ɑ/ versus /æ/ versus /i/), Time Point (Midpoint versus Edge), Consonant (/f/ versus /r/), and Direction (Anticipatory versus Carryover) as fixed factors. The full results of each model, including the interactions included in the final model, are reported in Appendix C. Selected results and post-hocs are reported in § 3.3.3.1.3 and § 3.3.3.2.3. Finally, § 3.3.3.2.4 and § 3.3.3.2.5 contain follow-up analyses evaluating unexpected harmonization and coarticulation restricted to trigger /i/, which did not suffer from unexpected harmonization. All models were carried out in SPSS v. 24.0 (IBM Corp, 2016) or v. 25.0 (IBM Corp, 2017), and the code used for each mixed model is provided in Appendix D.

3.3.3. Results

3.3.3.1. Height coarticulation

3.3.3.1.1. At vowel edge

The model for height coarticulation at vowel edge in Tatar included significant main effects for Target, Trigger, and Consonant, showing that vowel acoustics were impacted by vowel identity, VV coarticulation, and CV coarticulation respectively. The main effect of Direction was not significant, indicating that, on a global level, no difference existed between stimuli included in the design to measure anticipatory VV coarticulation and those designed to measure carryover effects. (This does not indicate that there was no difference in coarticulation across directions, a quality analyzed through the interaction of Direction and Trigger.) In this section, I explore these effects and the results of key interactions in greater depth.

The significant main effect of Target ($F(1, 1709.299) = 431.260$, $p < .001$) confirmed that the two target vowels /ɑ/ and /æ/, both classified phonologically as low vowels, nonetheless display phonetic differences with regard to height, as already demonstrated in § 3.2.2.1 above. The target vowel /ɑ/ generally had a higher normalized F1 ($M = -0.293$) than /æ/ ($M = -0.385$), pointing to a more open articulation for /ɑ/.

The significant main effect of Trigger ($F(2, 1709.191) = 100.382$, $p < .001$), accompanied by significant differences between all Trigger vowels ($p < .001$ for all comparisons), pointed to widespread vowel-to-vowel coarticulation in height across vowel pairs. Mean normalized F1 was highest for trigger /ɑ/ at -0.302, followed by trigger /æ/ at -0.336, and finally trigger /i/ at -0.376;

thus, vowels preceded or followed by /ɑ/ had the lowest articulation (on average), followed by those neighboring /æ/ and then /i/.

The significant main effect of Consonant (F(1, 1709.455) = 76.135, p < .001) indicated consonant-to-vowel (CV) coarticulation. Vowels next to /f/ generally had a lower F1 (M = -0.308) than those abutting /r/ (M = -0.363). The main effect of Direction was not significant (F(1, 1709.005) = 2.974, p = .085); since all anticipatory vowels appeared in the first syllable and all carryover targets in the second, this demonstrates that vowel height did not undergo acoustic change across the two syllables, at least not when examining both target vowels together.

One key interaction was the significant two-way relation between Target and Trigger (F(2, 1709.161) = 31.884, p < .001). Pairwise comparisons for the effect of Trigger within each target vowel were significant for all canonical-coarticulated vowel pairs. (See Figure 17.) This interaction and associated comparisons demonstrated that, while coarticulation existed between all target-trigger pairs tested, the magnitude of coarticulation varied across vowel pairs.

The three-way interactions between Consonant, Target, and Trigger (F(5, 1709.185) = 19.705, p < .001) and Direction, Target, and Trigger (F(5, 1709.071) = 12.794, p < .001) were

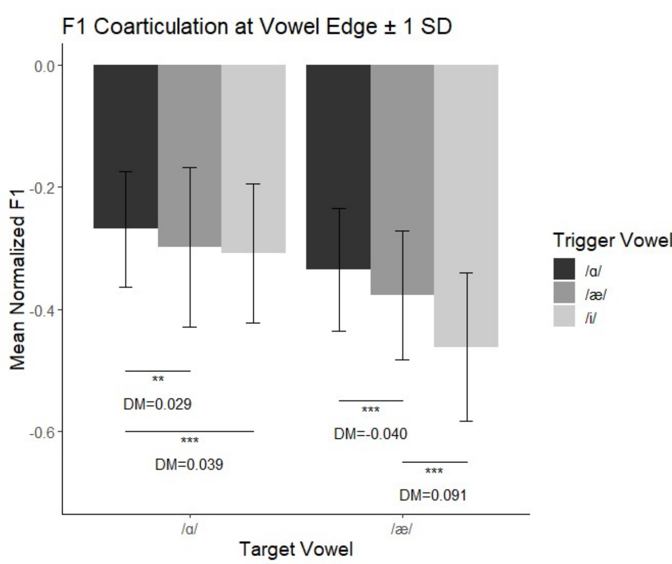

Figure 17: Target Vowel by Trigger Vowel interaction in F1 at vowel edge in Tatar. Shorter bars indicate lower vowels. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates p < .001, ** indicates p < .01, and * indicates p < .05. DM denotes "difference in means."

both significant, along with the four-way interaction between Consonant, Direction, Target, and Trigger ($F(5, 1709.043) = 25.014$, $p < .001$). Pairwise comparisons for the effect of Trigger at each level of Direction, Target, and Consonant, computed with Bonferroni adjustment, showed that significant anticipatory and carryover coarticulation occurred across several vowel-consonant combinations, as shown in Figure 18. In both directions, coarticulation was detected under more conditions with /r/ than with /f/ and when the target was /æ/ than when it was /ɑ/.

One result from the pairwise comparisons was particularly unexpected. The significant change to F1 of the /æ/ of /ɒfæt/ compared to the canonical V_2 of /sæfær/ is in the dissimilatory

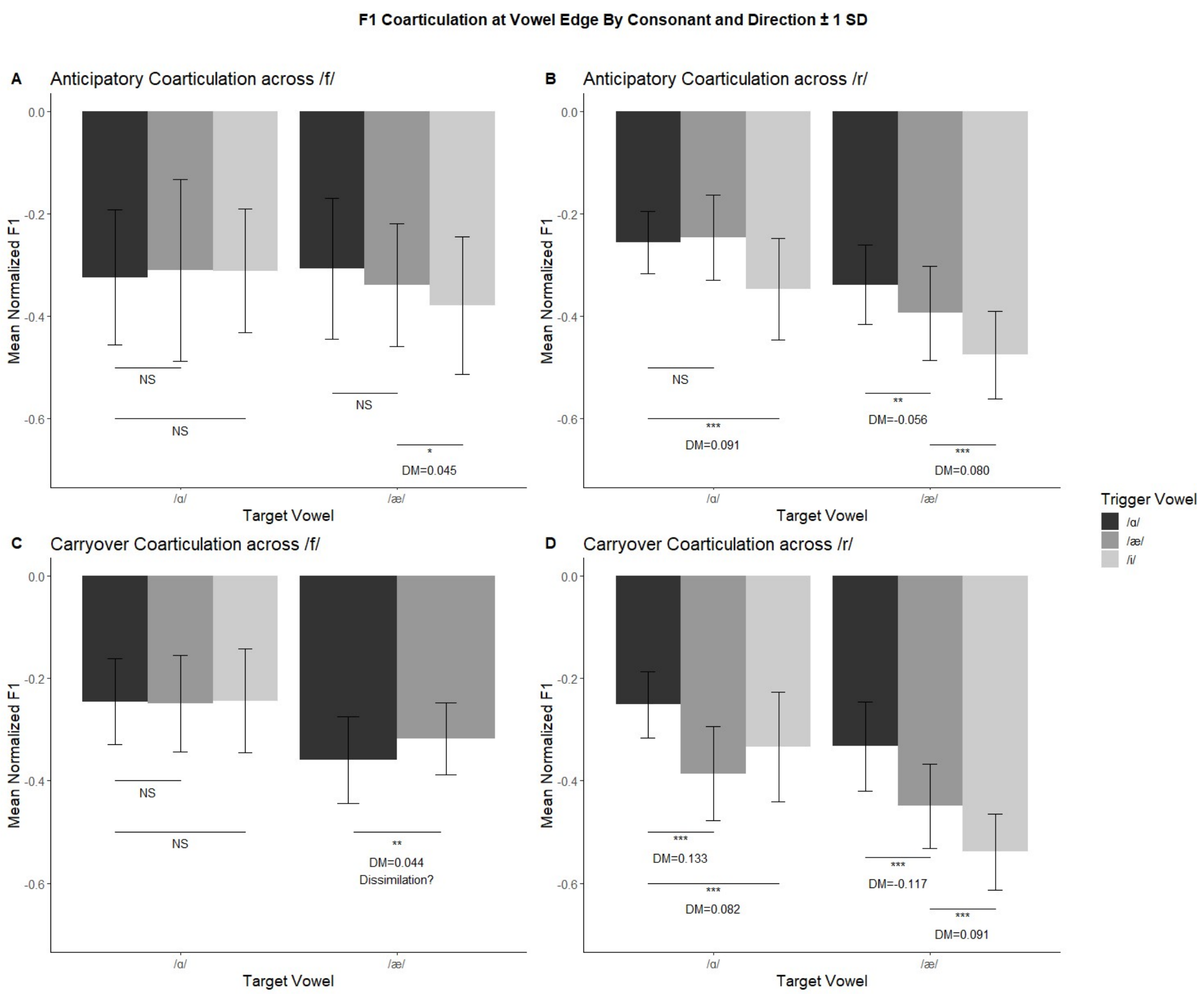

Figure 18: Effect of Trigger Vowels /ɑ/, /æ/, and /i/ on Target Vowels /ɑ/ and /æ/ across /f/ and /r/ on F1 in the anticipatory and carryover directions at vowel edge in Tatar. Shorter bars indicate lower vowels. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$. DM denotes "difference in means."

rather than the coarticulatory direction: [æ] in /ɒfæt/ is higher instead of lower, compared to the second [æ] in /sæfær/. This unexpected effect can be explained by the frequently encountered complete harmonization of /ɒfæt/ to [æfæt]. When /ɒfæt/ is fully harmonized, as it frequently was, the trigger /ɑ/ disappears altogether. Thus, the statistical effect is not so much measuring the effect of /ɒ/ on /æ/ in /ɒfæt/ as it was comparing the acoustic quality of /æ/ in [æfæt] to its quality in /sæfær/. Understood this way, the effect should be taken not as an instance of VV coarticulation but as a commentary on the combined effect of CV coarticulation and (perhaps) hyper- or hypoarticulation. (It seems particularly likely, given the lack of correspondence between the orthography and phonology, that productions of /ɒfæt/ as [æfæt] may demonstrate greater hyperarticulation than the control word.)

3.3.3.1.2. At vowel midpoint

The Tatar height model for vowel midpoint measurements included significant effects of Target and Direction and non-significant effects of Trigger and Consonant.

The significant main effect of Target ($F(1, 1699.176) = 573.899$, $p < .001$) pointed to the key role of vowel identity in shaping vowel acoustics. The mean F1 value was higher for target /ɑ/ ($M = -0.202$) than /æ/ ($M = -0.287$), indicating that /ɑ/ in Tatar is articulated lower than /æ/.

The remaining main effects exhibited notable differences from the edge results. Unlike in the vowel edge model, the main effects of Trigger ($F(2, 1699.163) = 2.541$, $p = .079$) and Consonant ($F(1, 1699.239) = 2.195$, $p = .139$) were not significant at vowel midpoint. Thus, overall, VV and CV coarticulation were acoustically reduced to the point of statistical non-significance by vowel midpoint. Thus, neither the consonantal context nor the neighboring vowel had a strong impact on F1 at midpoint; their influence dwindled over the 40% of vowel duration between midpoint and edge measurements.

In a third reversal from the edge model, the main effect of Direction was significant ($F(1, 1699.106) = 74.432$, $p < .001$); F1 was higher in the carryover direction ($M = -0.226$) than the anticipatory direction ($M = -0.258$). This main effect does not correspond to the role of Direction in vowel-to-vowel coarticulation, since F1 alone does not embody coarticulation. The effect of Direction does point to allophonic differences inherent in syllable division. In the disyllabic stimuli measured here, the two levels of Direction correspond perfectly to the first (unstressed) and second (stressed) syllables: anticipatory coarticulation was always measured on V_1 and carryover on V_2. Thus, the lower F1 (averaged across target vowels) found in the anticipatory direction corresponds to unstressed, first-syllable target vowels, while the higher F1 in carryover target vowels encompasses only stressed, second-syllable vowels. As shown in Figure 14 in § 3.2.2.3, first-syllable /æ/ generally had a higher F1 than second syllable /æ/, while first-syllable /ɑ/ had a much lower F1 (reflecting a higher articulation) than second-syllable /ɑ/, reflecting the established allophonic difference between [ɒ] and [ɑ]. The fact that this difference arose in the midpoint model, but not the edge model, poses no difficulty, since the midpoint model is expected to capture formant values from the central, steady-state portion of the vowel, where allophonic differences appear most strongly, while the edge values embody greater variation due to the flanking consonant and vowel. Thus, the global difference in Direction across target vowels can be attributed to the allophonic difference in /ɑ/, where a large difference in formant values across categories obscures the smaller difference in the opposite direction displayed by /æ/.

The array of significant results in interactions and pairwise comparisons in the F1 midpoint model provide greater insight into the patterns in height coarticulation present in the current data. Just as with the main effects, the results of the midpoint model did not directly parallel the edge model with regard to interactions, though some similarities do emerge. The

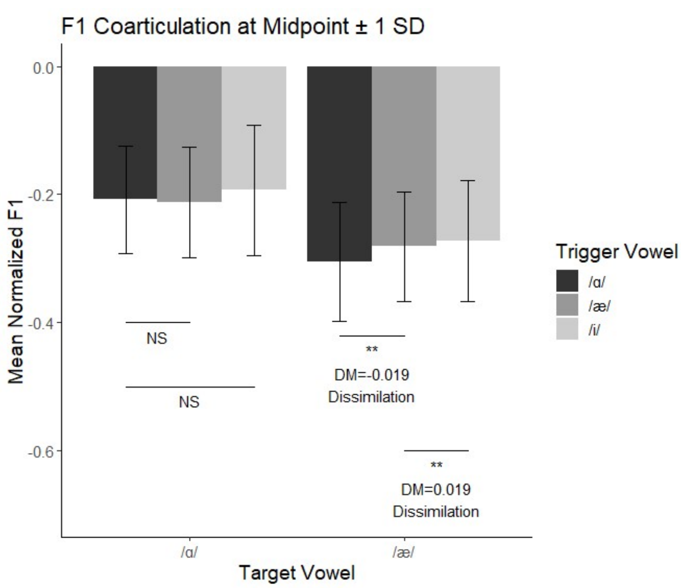

Figure 19: F1 coarticulation at vowel midpoint in Tatar. Shorter bars indicate lower vowels. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$. DM denotes “difference in means.”

interaction between Target and Trigger was significant (F(2, 1699.193) = 12.595, $p < .001$). Pairwise comparisons showed a significant effect between the canonical condition and both Trigger /ɑ/ (MD = -0.019, $p < .01$) and Trigger /i/ (MD = 0.019, $p < .01$) for Target /æ/; no significant effects emerged for Target /ɑ/. (See Figure 19.) However, unlike at vowel edge, both significant effects for target /ae/ were in the opposite to expected direction: the articulatory height of /æ/ rose under the influence of trigger /ɑ/ and lowered near trigger /i/. Thus, F1 assimilation between vowels did not persist to vowel midpoint for target /ɑ/ and reversed direction, becoming dissimilatory, for target /æ/.

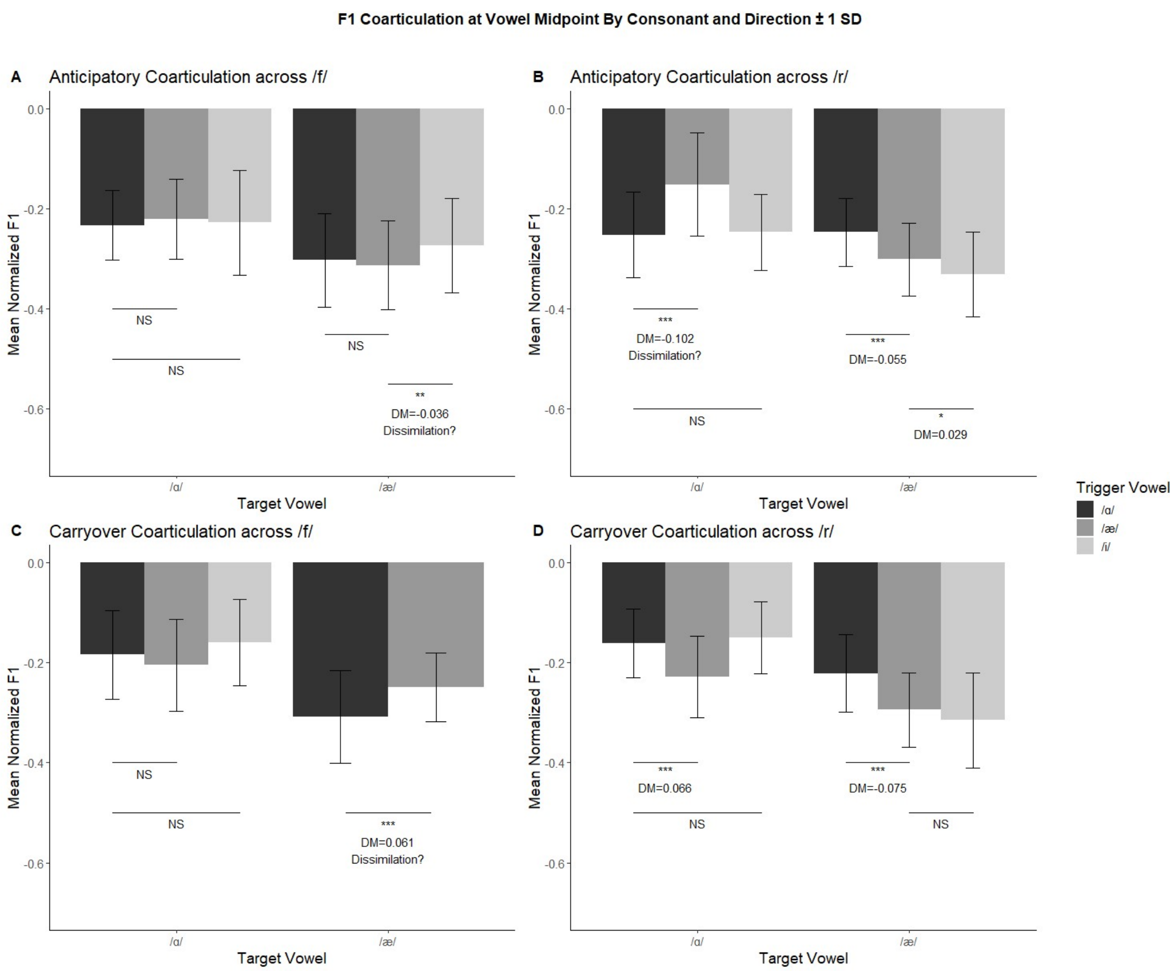

Figure 20: Effect of Trigger Vowels /ɑ/, /æ/, and /i/ on Target Vowels /ɑ/ and /æ/ across /f/ and /r/ on F1 in the anticipatory and carryover directions at vowel midpoint in Tatar. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$. DM denotes “difference in means.”

The two three-way interactions were again significant, as recounted in Appendix C, but I will focus primarily on the four-way interaction Consonant, Direction, Target, and Trigger ($F(5, 1699.084) = 11.731$, $p < .001$). The significance of pairwise comparisons for Trigger in each condition is shown in Figure 20. The unexpected dissimilation of /ɒfæt/ present in the vowel edge model persisted, as did several of the significant coarticulatory effects. Three effects present in the edge model (target /ɑ/ and trigger /æ/ across /r/, anticipatory; target /ɑ/, trigger /i/, carryover; and target /æ/, trigger /i/ across /r/, carryover) were not significant in the midpoint model, suggesting that the VV coarticulatory effect was not of sufficient duration to be detected at midpoint. Finally, the anticipatory comparison between target /ɑ/ and trigger /æ/ across /r/, which was not significant at vowel edge, became significant at midpoint, perhaps because it was overpowered by CV coarticulation closer to the consonant boundary. The implications of these results will be explored more fully in § 3.3.4.1.

3.3.3.1.3. F1 magnitude model

The model evaluating magnitude took F1 difference scores as its dependent variable in order to evaluate differences in the magnitude of coarticulation across conditions. (The method used to calculate difference scores is explained in § 2.2.5.2 and § 3.3.2.3.) Whereas the previous models relied on the effect of Trigger to detect statistically significant VV coarticulation, the magnitude model assumes the presence of coarticulation and aims only to seek statistically significant differences in magnitude of coarticulation. The full results of the model are reported in Appendix C, and key results are reported here.

Significant differences existed for each of the five main effects tested: with regard to Target ($F(1, 3442.432) = 24.112$, $p < .001$), the vowel /æ/ coarticulated more strongly ($M = 0.025$) than target /ɑ/ ($M = 0.008$). This result complements the significant Target by Trigger interaction found in both the edge and midpoint models, which indicated variation in coarticulatory magnitude across target vowels. Similarly, differing trigger vowels induced coarticulation to various degrees: the greatest F1 coarticulation was induced by Trigger /i/ ($M = 0.031$), followed by /ɑ/ ($M = 0.015$) and finally /æ/ ($M = 0.005$; main effect of Trigger $F(2, 3441.130) = 15.590$, $p < .001$), an intuitive result since [i] as a trigger differs more in height from both targets than the remaining trigger-target pairs differ from one another. Target also interacted significantly with Trigger in the magnitude model ($F(2, 3441.222) = 20.444$, $p < .001$), demonstrating that the efficacy of individual triggers depended on the target in question. In post-hoc pairwise comparisons, only trigger /i/ increased coarticulation over the canonical condition for target /ɑ/; for target /æ/, flanking /ɑ/ triggered greater coarticulation than the canonical condition, and trigger /i/ increased coarticulation over both /ɑ/ and the canonical conditions, as shown in Figure 21. (Note that the canonical condition represents the difference between the canonical grand mean for that speaker and vowel and a particular canonical utterance; while all difference scores in the canonical condition are expected to approximate 0, the naturally high degree of variability in formant values ensures that the exact score of 0 never appears.) Also notable is the extreme variation in coarticulatory magnitude, visible in the error bars displaying one standard deviation above and below the mean. The wide spread of these standard deviations underscores the reality that coarticulation data is highly variable across speakers and utterances.

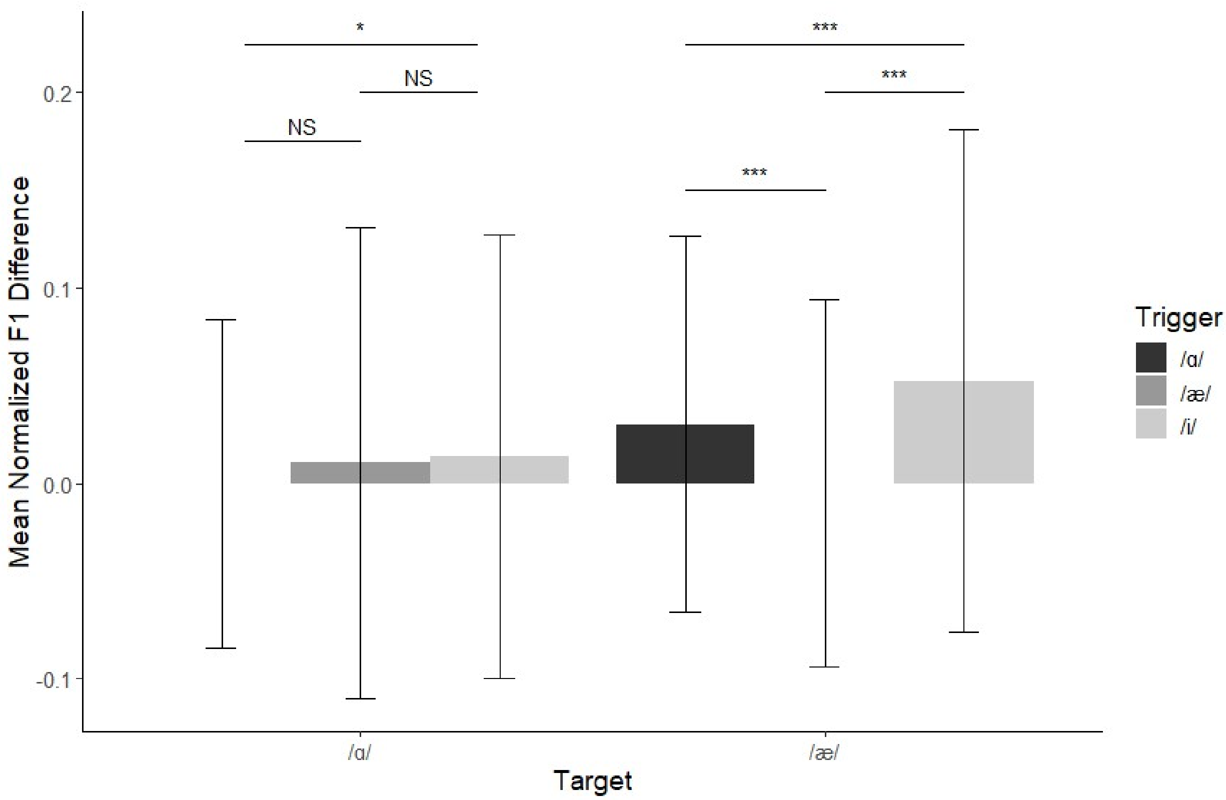

Figure 21: F1 difference scores by target vowel and trigger vowel, indicating magnitude of coarticulation, in Tatar. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$. Canonical means approach zero and are thus not visible on the graph, but their error bars display the variation in values.

Two of the remaining significant main effects belonged to Direction and Consonant, showing that the magnitude of F1 coarticulation varied across conditions for both of these factors. With regard to Direction, anticipatory coarticulation (M = 0.023) had a greater magnitude than carryover coarticulation (M = 0.010; $F(1, 3440.134) = 24.824$, $p < .001$), while for Consonant, VV coarticulation across intervening /r/ (M = 0.032) was greater than across intervening /f/ (M = -0.001; $F(1, 3442.903) = 114.708$, $p < .001$). Additionally, the effect of Time Point was significant: coarticulation was greater at vowel edge (M = 0.052) than at vowel midpoint (M = -0.019; $F(1, 3439.256) = 610.676$, $p < .001$). Thus, the magnitude model demonstrated that F1 coarticulation was greater for target /æ/ than /ɑ/, in the anticipatory direction than the carryover, at edge than at midpoint, across /r/ than /f/, and when triggered by /i/ than /ɑ/ and /ɑ/ than /æ/.

3.3.3.2. Backness coarticulation

3.3.3.2.1. At vowel edge

The two models analyzing backness coarticulation used normalized F2 as their acoustic cue and dependent variable, bundling the differences in backness among /ɑ/, /æ/, and /i/ and the difference in rounding between initial and noninitial /ɑ/ into a single acoustic parameter. In the F2 model at vowel edge, vowel acoustics were significantly impacted by vowel identity (Target), VV coarticulation (Trigger), and intervening consonant identity (Consonant), but not syllable (Direction). Statistically speaking, the main effects of Target ($F(1, 1709.791) = 2739.921$, $p < .001$), Trigger ($F(2, 1709.594) = 520.696$, $p < .001$), and Consonant ($F(1, 1710.072) = 554.195$, $p < .001$) were significant, and the main effect of Direction was not ($F(1, 1709.259) = 3.231$, $p = .072$).

With regard to target vowel, /ɑ/ generally had a lower F2 (M = -0.472) than /æ/ (M = 0.766), as expected given their relative positions in the vowel space (/ɑ/ is more back than /æ/). With regard to Trigger, the lowest F2 found in vowels affected by Trigger /ɑ/ (M = 0.495), followed by Trigger /i/ (M = 0.657) and then Trigger /æ/ (M = 0.692). (This strong effect of /æ/ is attributed to unexpected harmonization, discussed in § 3.3.4.3.) Pairwise comparisons with Bonferroni adjustment between the canonical and coarticulated conditions were significant for all target-trigger combinations, suggesting widespread vowel-to-vowel coarticulation. However, as these numbers represent averages across target vowels and are therefore subject to influence by the number of utterances available for analysis for each vowel, they point to only the most general and overarching of trends. With regard to Consonant, target vowels near /f/ had a lower F2 (M = 0.530) than those near /r/ (M = 0.688). The lack of a significant main effect for Direction indicated that there was no acoustic change across syllables (since anticipatory coarticulation was always measured in V_1 and carryover in V_2).

The magnitude of coarticulation across target-trigger pairs was explored through the two-way interaction between Target and Trigger, which was significant ($F(2, 1709.541) = 176.287$, $p < .001$). Post-hoc tests with Bonferroni adjustment showed that all pairwise comparisons for Trigger within both Target /ɑ/ and Target /æ/ were significant, as shown in Figure 22. The significance of the interaction indicates that the magnitude of coarticulation differed significantly across target-trigger pairs; the differences in means revealed in the pairwise comparisons and the results of the magnitude model (see § 3.3.3.2.3 below) show that /ɑ/ underwent greater assimilatory effects than /æ/.

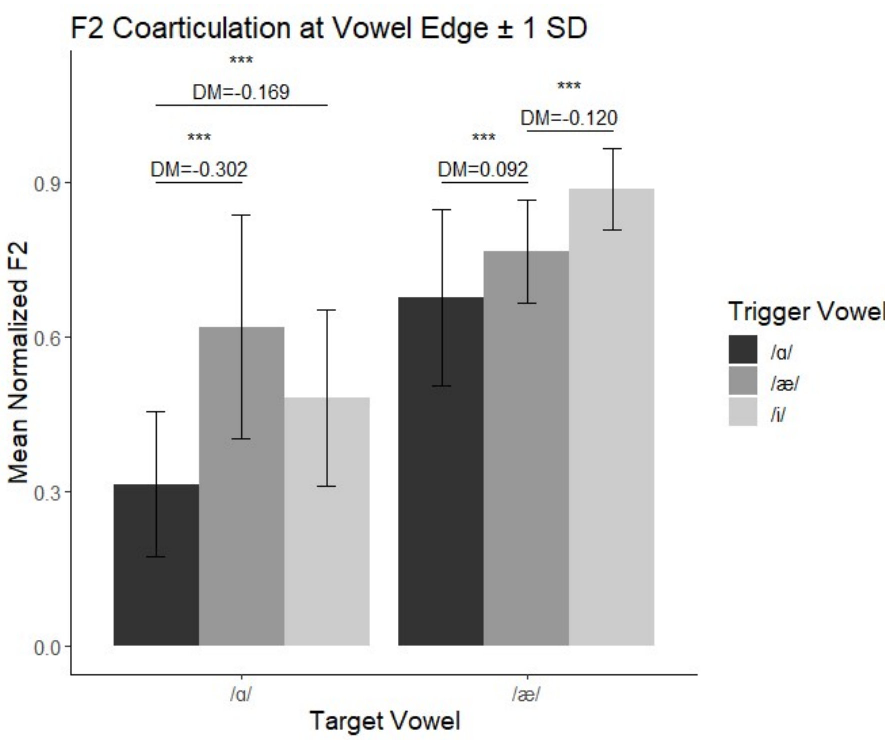

Figure 22: F2 coarticulation by Target and Trigger Vowel at vowel edge in Tatar. Shorter bars indicate more retracted vowels. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates p < .001, ** indicates p < .01, and * indicates p < .05. DM denotes "difference in means."

More complex interactions involving Target and Trigger examined how VV coarticulation varied across conditions of Consonant and Direction. The interactions between Consonant, Target, and Trigger ($F(5, 1709.583) = 27.503$, $p < .001$), Direction, Target, and Trigger ($F(5, 1709.378) = 47.240$, $p < .001$), and Consonant, Direction, Target, and Trigger ($F(5, 1709.326) = 53.437$, $p < .001$) were all significant, and the means for each condition are displayed in Figure 23. Pairwise comparisons showed that assimilation was possible between all vowel pairs regardless of intervening consonant identity. Trigger /i/ tended to have a fronting effect on neighboring /æ/, as expected given their relative positions in the vowel space. (See

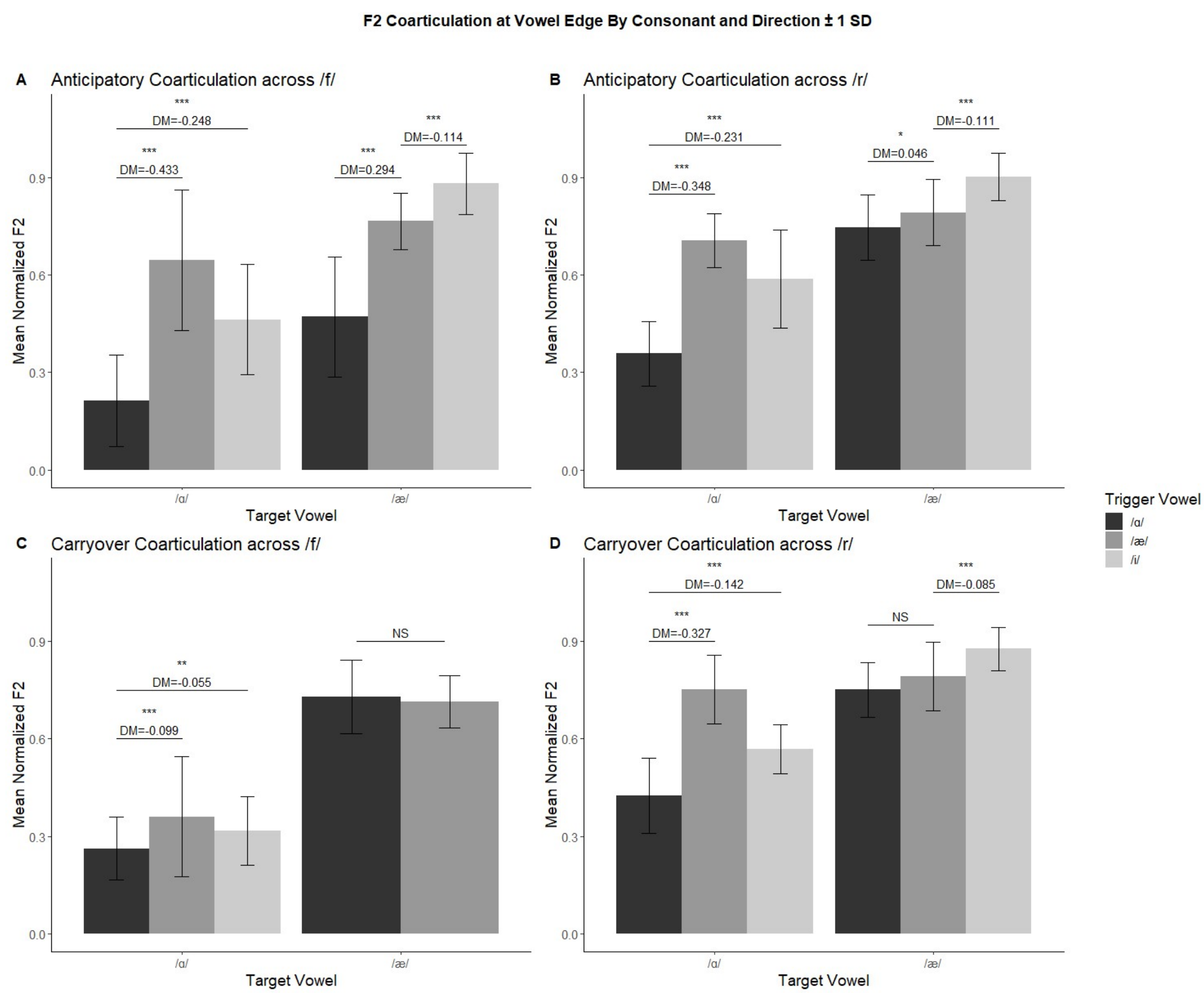

Figure 23: Effect of Trigger Vowels /ɑ/, /æ/, and /i/ on Target Vowels /ɑ/ and /æ/ across /f/ and /r/ on F2 in the anticipatory and carryover directions at vowel edge in Tatar. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$. DM denotes "difference in means."

Figure 13 and Table 8 for evidence of their usual relative arrangement in the Tatar vowel space; while /i/ and /æ/ are both phonologically front vowels, /i/ has a much higher F2.) Carryover coarticulation between trigger /ɑ/ and target /æ/ (target words /ɒfæt/ and /gɒræp/) was notably lacking; this gap is discussed in § 3.3.4.3.

3.3.3.2.2. At vowel midpoint

In the F2 model for measurements taken at vowel midpoint, target vowel identity, trigger vowel identity, intervening consonant identity, and syllable number (realized via the factor Direction) all influenced F2. With regard to target vowel identity, the main effect of Target was significant ($F(1, 1699.950) = 3129.868$, $p < .001$): Target /æ/ generally had a higher F2 ($M = 0.784$) than /ɑ/ ($M = 0.465$), as expected, reflecting its more fronted position in the vowel space. The main effect of Trigger was also significant ($F(2, 1699.871) = 263.935$, $p < .001$), and target vowels near Trigger /ɑ/ had the most back articulation ($M = 0.541$), followed by those near /i/ ($M = 0.618$) and then /æ/ ($M = 0.694$). (This order mirrored the one found in the F2 edge model; while it is surprising that vowels flanked by /i/ had a lower F2 than those near /æ/, creating the appearance that /i/ was not as strong a coarticulatory trigger as /æ/, despite /i/ having a higher F2, this unexpected effect can also be attributed to unexpected harmonization, which intensified the influence of /æ/ on /ɑ/ beyond its expected range. This is discussed further in § 3.3.4.3.) Post-hoc comparisons with Bonferroni adjustment showed significant differences between all three levels of Trigger, signaling significant VV coarticulation across trigger vowels. Additionally, the main effect of Consonant was significant ($F(1, 1700.329) = 62.099$, $p < .001$), with vowels near /f/ demonstrating a lower F2 ($M = 0.584$) than those near /r/ ($M = 0.648$), just as at vowel edge. Unlike at vowel edge, the main effect of Direction was also significant ($F(1, 1699.534) = 5.124$, $p < .001$): F2 was higher for carryover (second-syllable) vowels ($M = 0.632$) than anticipatory (initial) vowels ($M = 0.605$); this may relate to the unexpected harmonization discussed in § 3.3.4.3.

The significant Target by Trigger interaction ($F(2, 1700.059) = 186.347$, $p < .001$), indicated that the magnitude of coarticulation differed across target-trigger pairs. Post-hoc pairwise comparisons showed significant differences between all pairs, though the means varied dramatically, as shown in Figure 24. Notably, the effect of /i/ on target /ɑ/ was limited, perhaps

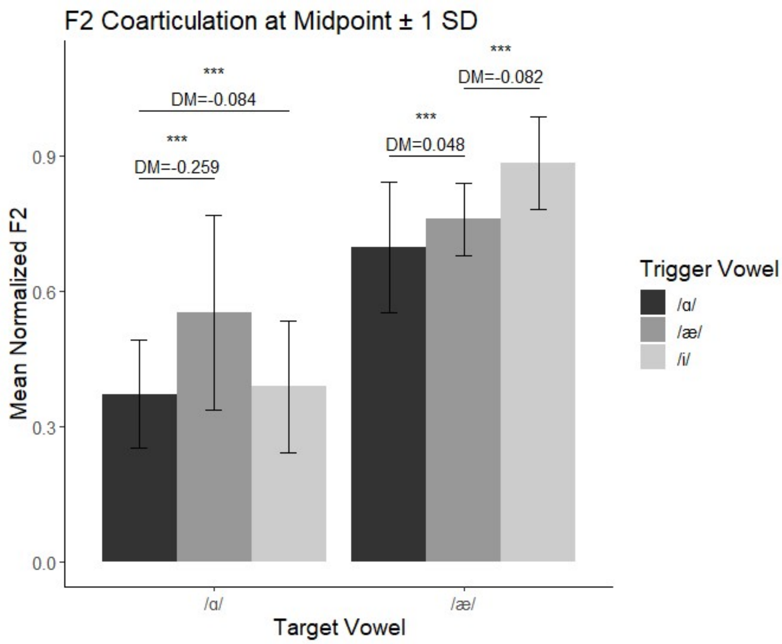

Figure 24: F2 Coarticulation by Target and Trigger Vowel at vowel midpoint in Tatar. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$. DM denotes "difference in means."

because the two vowels differed in two dimensions, height and backness, rather than just one, as the /i/ - /æ/ and /æ/ - /ɑ/ pairs do.

As in the earlier models, the interactions between Consonant, Target, and Trigger ($F(5, 1699.784) = 18.023$, $p < .001$), Direction, Target, and Trigger ($F(5, 1699.603) = 37.082312$, $p < .001$), and Consonant, Direction, Target, and Trigger ($F(5, 1699.401) = 39.378$, $p < .001$) were significant; pairwise comparisons of Trigger under each condition are shown in Figure 25. The comparisons depicted in this figure show that significant anticipatory coarticulation occurred between target /ɑ/ and trigger /æ/ across both /f/ and /r/, target /ɑ/ and trigger /i/ across /r/, target /æ/ and trigger /ɑ/ across /f/, and target /æ/ and trigger /i/ across both /f/ and /r/. Carryover effects were significant for target /ɑ/ and trigger /æ/ across /f/ and /r/, target /ɑ/ and trigger /i/ across /r/, and target /æ/ and trigger /i/ across /r/. The non-significant effects are equally important: the lack of carryover assimilation between /ɑ/ and /æ/ across /f/, for example, accompanies the extreme anticipatory assimilation of /ɑ/ to /æ/ across /f/, completing a fuller picture of the near-complete assimilation present in the target word /ɒfæt/. The challenges of differentiating coarticulation from harmonization are discussed in § 3.3.4.3.

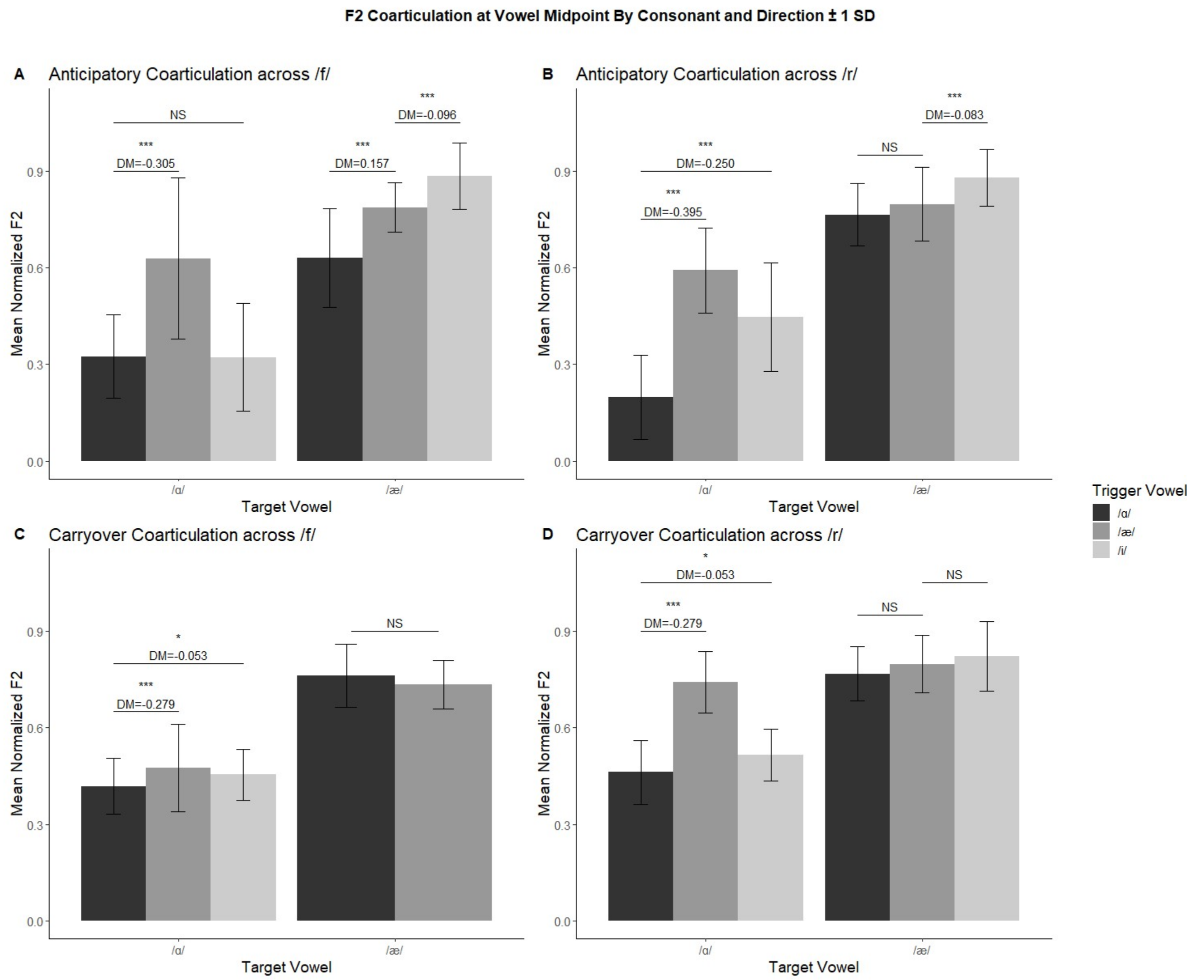

Figure 25: F2 coarticulation at vowel midpoint by consonant and direction in Tatar. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates p < .001, ** indicates p < .01, and * indicates p < .05. DM denotes “difference in means.”

3.3.3.2.3. F2 magnitude model

In the F2 magnitude model, which used F2 difference scores as its dependent factor (as explained in § 3.3.2.3), magnitude of coarticulation varied by target vowel identity, trigger vowel identity, direction of coarticulation, intervening consonant identity, and time point. Thus, all five main effects were significant: Target ($F(1, 3435.670) = 429.643$, $p < .001$), Trigger ($F(2, 3435.144) = 265.620$, $p < .001$), Direction ($F(1, 3434.587) = 22.534$, $p < .001$), Consonant ($F(1, 3436.099) = 187.503$, $p < .001$), and Time Point ($F(1, 3434.063) = 6.294$, $p = .012$). As expected, coarticulation decreased from edge ($M = 0.103$) to midpoint ($M = 0.088$). F2 coarticulation was also greater for target /ɑ/ (M = 0.135) than /æ/ (M = 0.053), unlike for F1 coarticulation, where target /æ/ had a greater magnitude of coarticulation compared to target /ɑ/. (The notable differences in magnitude between backness and height coarticulation are expected given the far more restricted range of F1 and do not necessarily correspond to any meaningful difference in magnitude of coarticulation across dimensions.) The greatest coarticulation was induced by trigger /æ/ (M = 0.139), followed by /i/ (M = 0.115) and then /ɑ/ (M = 0.036), despite the expectation of greater fronting from /i/, the most fronted of the three triggers. The interaction between Target and Trigger explores the differences in coarticulatory magnitude across vowel pairs in greater depth. This interaction was significant ($F(2, 3435.160) = 773.172$, $p < .001$), indicating that magnitude of coarticulation depended on both the target and the trigger. It is expected that coarticulatory magnitude will be least in the canonical condition, when target and trigger are identical, and this was indeed true: post-hoc pairwise comparisons revealed that for target /ɑ/, the greatest coarticulation was induced by /æ/, followed by /i/ and then the canonical condition, while for target /æ/, the strongest trigger was /i/, followed by /ɑ/ and then canonical. (See Figure 26; canonical difference scores approach zero, as is expected since they reflect the

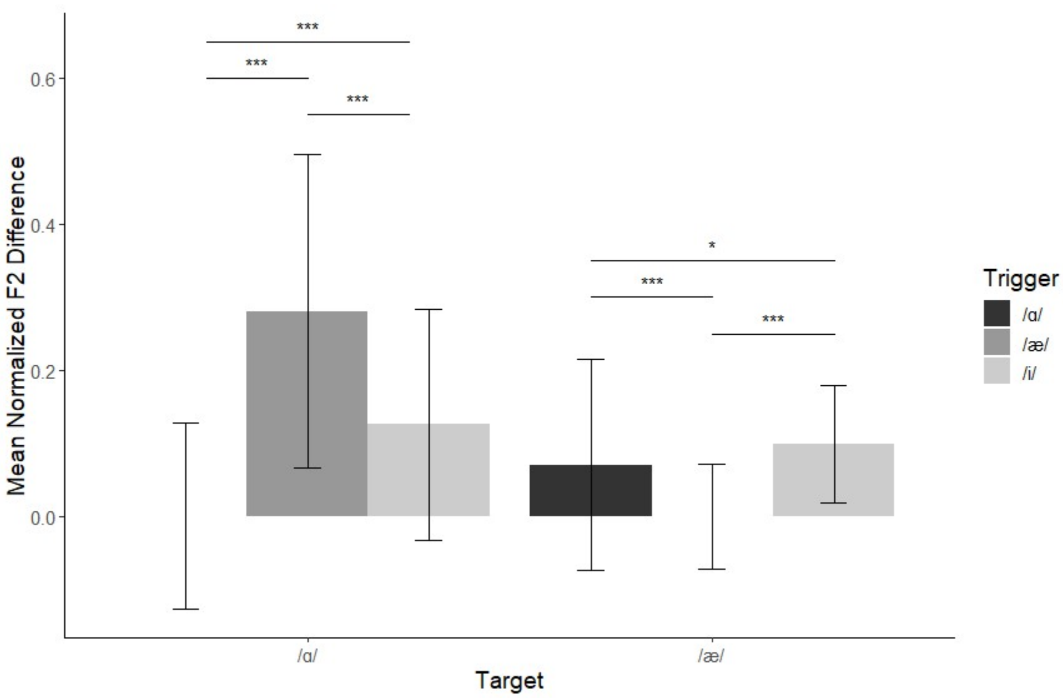

Figure 26: F2 difference scores by target vowel and trigger vowel, indicating magnitude of coarticulation, in Tatar. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$. Canonical means approach zero and are thus not visible on the graph, but their error bars display the variation in values.

mean offset of individual canonical utterances from the canonical mean.) This hierarchy reflects the overwhelming impact of unexpected harmonization, wherein complete assimilation of a far greater magnitude than mere coarticulation was observed in fully or partially harmonized utterances. Since this unexpected harmonization was primarily observed between /æ/ and /ɑ/ (see § 3.3.4.3), it naturally leads to the appearance of greater coarticulation between these vowels than with /i/.

As in the F1 magnitude model, pairwise comparisons for Direction and Consonant revealed stronger coarticulation in the anticipatory direction ($M = 0.103$) than the carryover direction ($M = 0.088$) and across intervening /r/ ($M = 0.121$) compared to /f/ ($M = 0.068$). Numerous significant interactions were included in the model and are available for more fine-grained analysis, but since many, if not all, of these findings are due to specific lexical effects, I will address them (albeit indirectly) in § 3.3.3.2.4 and § 3.3.4.3. As for previous models, a summary of all significant effects and interactions is available in Appendix C, and the code is provided in Appendix D.

To summarize, the F2 magnitude model found a greater magnitude of coarticulation at vowel edge than midpoint, in the anticipatory direction than carryover, across /r/ than /f/, and in target /ɑ/ than /æ/. However, although this model was distorted by the presence of unexpected harmonization and should not be trusted, the key trends accurately reflect Tatar VV coarticulation, as demonstrated in the more reliable model presented in § 3.3.3.2.5.

3.3.3.2.4. Tests evaluating unexpected harmonization

During data annotation, it became clear that many participants were producing target words intended as disharmonic in a fully harmonized fashion, with complete assimilation across root vowels that was both clearly audible in the recording and clearly visible in the spectrogram (no change in formants across syllables). The affected target words were primarily /ɑ/-/æ/ and /æ/-/ɑ/ disharmonic words measuring backness coarticulation, though in some utterances of target words combining /ɑ/ and /i/, /i/ seemed to be backed under the influence of /ɑ/ enough to merit transcription as /ɨ/. Because the planned analyses reported in § 3.3.3.1 - § 3.3.3.2.3 only compare formants across the canonical and coarticulated conditions, they are not suited to detecting instances of harmonization or to differentiating complete harmonization from partial assimilation or minor coarticulation. To compare formant values within words, I conducted four tests examining the F2 values of the first- and second-syllable vowels at midpoint – one test for each of the [ɒCæ] and [æCɑ] items. Due to skew, lack of normality, or heteroscedasticity, a non-parametric Mann-Whitney U test was used to evaluate the items /ɒfæt/, /gɒræp/, and /ʑæfɑ/, and an independent t-test was run to examine /ʃærɑb/. Bonferroni adjustment (ɑ/4) was applied to the ɑ-level to counteract the inflating effects of running separate tests; thus, the tests were only considered significant if the p-value was less than .0125. Each test compared the F2 values of first-syllable vowels to second-syllable vowels to determine whether the two vowels differed significantly in backness; results are given in Table 12. As can be seen, only two of the four lexical items, /ʃærɑb/ and /ɒfæt/, were reliably harmonized often enough to render its two vowels indistinguishable with regard to F2. This does not mean that harmonization did not occur in the other two lexical items, but it was mixed with enough instances of the expected disharmonic pronunciation that the model detected the distribution of formants for the two vowels as different.

Table 12: Pairwise comparisons for Word by Vowel interaction in Tatar. Non-significant differences across syllables indicate that word was reliably harmonized. Significant differences do not preclude harmonization, but indicate that it was not complete or was not widespread across utterances.

Word	Significant difference across syllables?	When assimilated, both vowels pronounced as:
/ɒfæt/	No (U = 2156, p = .035)	[æ] (V_2)
/gɒræp/	Yes (U = 563.5, p < .001)	[æ] (V_2)
/ʑæfɑ/	Yes (U = 1115, p < .001)	[ɑ] (V_2)
/ʃærɑb/	No (t (151) 1.479, p = .141, 95% CI [-0.008, 0.054])	[æ] (V_1)

3.3.3.2.5. Limited F2 magnitude model – trigger /i/

Due to the widespread harmonization found in [ɒCæ] and [æCɑ] items, a second F2 magnitude model was fitted; this smaller model evaluated coarticulation only in words with target /i/ to confirm whether the trends found in the first model held true when harmonization was not at play. The full model is reported in Appendix C; however, the key trends held true: the main effects of Target (F(1, 1025.239) = 29.549, p < .001), Direction (F(1, 1024.988) = 9.062, p = .003), Consonant (F(1, 1024.849) = 104.660, p < .001), and Time Point were all significant (F(1, 1024.045) = 5.810, p = .016). Pairwise comparisons indicated that coarticulation decreased from vowel edge (M = 0.113) to midpoint (M = 0.095), reflecting the pattern expected for coarticulation. VV coarticulation was greater for target /ɑ/ (M = 0.127) than /æ/ (M = 0.081), in the anticipatory direction (M = 0.116) than the carryover (M = 0.091), at vowel edge (M = 0.113) than midpoint (M = 0.095), and across /r/ (M = 0.147) than /f/ (M = 0.061). Thus, no unexpected reversals of key trends accompanied the removal of the four oft-harmonized items, demonstrating that these trends are reliable indicators of real coarticulatory patterns.

3.3.4. Discussion

3.3.4.1. Height coarticulation

The analysis of F1 coarticulation revealed assimilation in both directions: anticipatory and carryover effects were detected across a range of conditions. Anticipatory effects were significantly larger than carryover effects, suggesting a directional preference for anticipation over perseveration – that is, assimilation to the stressed vowel rather than to the unstressed one. Additionally, there is some evidence of a consonantal preference: /f/ was more effective at blocking VV effects across it than /r/, as demonstrated by the numerous conditions involving /f/ in which no significant effect emerged between target and trigger in the post-hoc tests and the significantly smaller values associated with /f/ in the magnitude model. This is surprising, since previous research has shown a tendency for labial consonants, particularly /p/ and /b/, to freely permit VV coarticulation, since the consonantal articulation involves no tongue body gestures to interrupt the continuous movement from one vowel to the next (Fowler & Brancazio, 2000; Modarresi et al., 2004). While it is tempting to generalize the findings of these studies to other labial consonants, including /f/, it is clear from the present results that such generalizations are inaccurate. Not only was /f/ particularly efficient at blocking VV coarticulation, it was also far more effective at blocking coarticulation than /r/ was. These effects are visible in the scatterplot provided in Figure 27, which contrasts the mean value for each lexical item with trigger /i/ to the canonical means.

The ability of /r/ to block or permit coarticulation may be tied to its allophonic realization. Three freely varying allophones of /r/ were observed in Tatar during data annotation: [r], [ɹ], and [ɾ]. While trilled [r] is taken to be the canonical pronunciation (Poppe, 1968), [ɾ] and [ɹ] were, impressionistically, far more common in the data. Recasens (1987) investigated VV

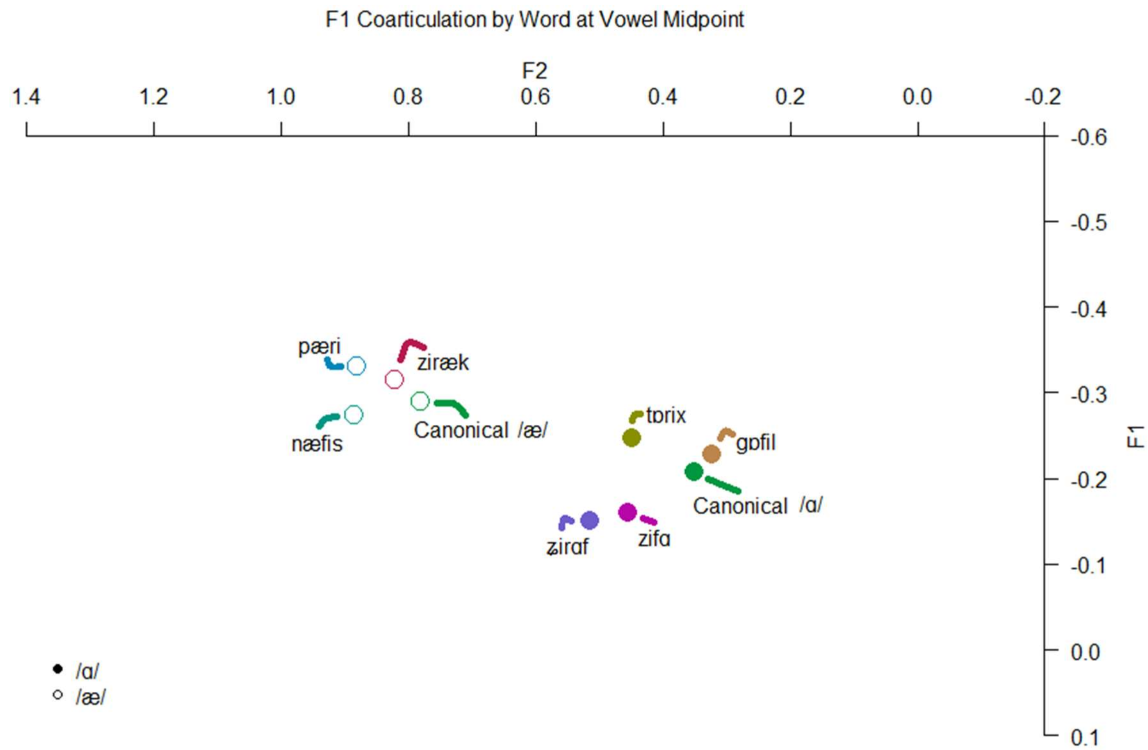

Figure 27: F2 x F1 scatterplot for Tatar items with trigger /i/ at vowel midpoint

coarticulation across [ɾ] and [r] in Spanish and Catalan and found that [ɾ] permitted greater VV coarticulation from the transconsonantal vowel than [r] did (at least in F2, the variable he studied). He attributed this difference to the degree of gestural commitment required of the tongue dorsum, which is higher for [r] with its repeating trill than for [ɾ]. Based on his results, it is plausible that many of the significant VV effects found across Tatar /r/ were influenced by utterances utilizing the [ɾ] or [ɹ] articulations rather than the trilled [r].

The preference for anticipation is not surprising, given the strong asymmetry between anticipatory and carryover effects found in Tatar by Conklin (2015); what is unexpected is the presence of carryover coarticulation in at least some conditions. This preference for anticipation supports Hypothesis 4, which tied word-final stress to coarticulatory anticipation, and suggests that, at least in Tatar, maintaining the integrity of stressed vowels in non-harmonizing words is a higher phonological priority than ensuring that harmony and coarticulation proceed in the same direction. It may also supply tentative support for the theory that harmony may help suppress coarticulation in the parallel direction – or at least, it provides further opposition to the prediction that harmony and coarticulation will always proceed in parallel.

In a few of the post-hoc comparisons, an unexpected result appeared: significant differences associated with the transconsonantal trigger vowel were in the dissimilatory, rather than coarticulatory, direction. This was the case for anticipatory coarticulation across /f/ between target /æ/ and trigger /i/ at vowel midpoint, as well as carryover coarticulation across /f/ between target /æ/ and trigger /ɑ/ at both midpoint and edge. Due to the stimuli design, each of these cases was tested with a single target word – /sæfær/ for the canonical vowel utterances, and /næfis/ and /ɒfæt/, respectively, for the coarticulated ones. In the case of coarticulation in the /æ/ of /næfis/, it is not clear why dissimilation should occur at vowel midpoint, when the expected coarticulation was significant at vowel edge, unless it is due to CV coarticulation with the initial /n/. For /ɒfæt/, however, this dissimilation is likely tied to the unexpected harmonization discussed in §3.3.4.3, which led to the common pronunciation [æfæt]. Given that the /ɑ/ of /ɒfæt/ was most often produced as /æ/, I propose that this harmonized /æ/ was subject to hyperarticulation by speakers attempting to make the vowel's identity particularly clear. The resultant overshoot would create the appearance of dissimilation, wherein the F1 value so far approached the canonical target that it, in fact, surpassed it.

In summary, F1 VV coarticulation in Tatar occurred in both directions, but most frequently and with the greatest magnitude in the anticipatory direction, suggesting that stress is a controlling factor in shaping VV coarticulation. Coarticulation was also more frequent across /r/ than /f/, perhaps due to the widespread use of the [ɹ] allophone, which permits greater coarticulation than the more canonical trilled [r]. The success of /f/ in blocking coarticulation is unexplained and represents a departure from previous studies' findings for other labial consonants. Finally, for two target words, significant effects were detected in the dissimilatory direction; the first of these is unexplained, while the second is attributed to lexically specified unexpected harmonization.

3.3.4.2. Backness coarticulation

In the F2 analysis, the unexpected harmonization found in many [ɒCæ] and [æCɑ] utterances obscures many of the underlying coarticulatory patterns. Where target vowels harmonized, they created the impression of extremely large coarticulatory effects in one direction, often with a corresponding missing effect in the other direction (although some of the [ɒCæ] and [æCɑ] items showed effects in both directions due to variability or centralization). Consider the frequent realization of [æfæt] in place of /ɒfæt/: this change accounts for the large anticipatory effect between target /ɑ/ and trigger /æ/ across /f/ and provides an explanation for the lack of a significant carryover effect between target /æ/ and trigger /ɑ/ across /f/. Figure 28 displays the /ae/ and /a/ means of these words in relation to the canonical means of each vowel. As can be seen, the vowels of /ʃærɑb/ (in red) are closely aligned, showing that harmonization was consistent and complete, while other lexemes display greater variation. Since the means in Figure 28 are averaged across both harmonized and non-harmonized utterances, they do not closely reflect the real formant values of any particular utterance or group of utterances, but instead provide a snapshot of the rate of harmonization by item. Items with closely-aligned target vowels, like /ʃærɑb/, were harmonized more consistently than those with a greater gap between vowels. Unexpected harmonization is discussed further in § 3.3.4.3 below.

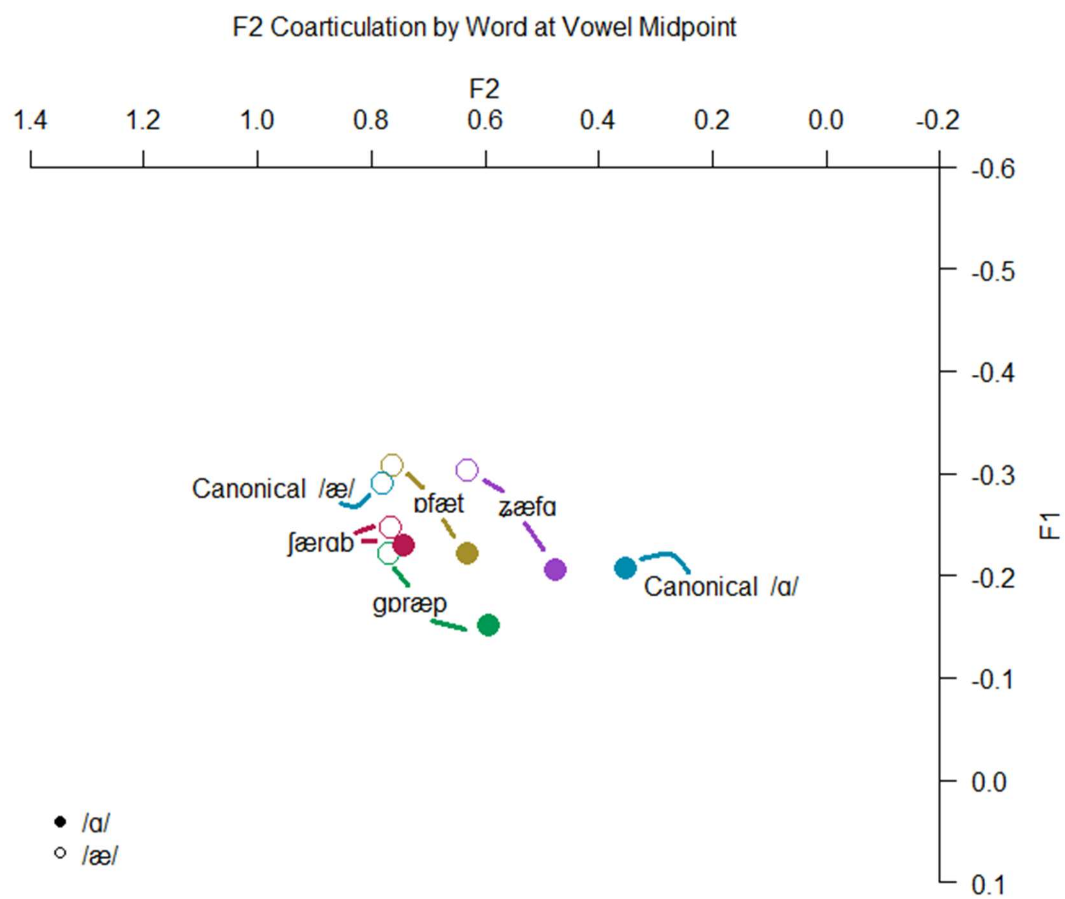

Figure 28: F2 x F1 scatterplot for [ɒCæ] and [æCɑ] items at vowel midpoint in Tatar

When the unexpected harmonization of [ɒCæ] and [æCɑ] items is filtered out to focus on assimilatory effects with trigger /i/, some of the same trends were found for F2 coarticulation as for F1: anticipatory coarticulation was always of a greater magnitude than carryover, and /r/ always permitted more coarticulation across it than /f/. However, the preference for target vowel is reversed across formants: target /æ/ is more susceptible to F1 coarticulation than /ɑ/, while /ɑ/ undergoes greater F2 assimilation than /æ/. This may be due in part to the fact that /æ/ and /i/ are both front vowels: they share close canonical F2 values, leaving little room for improvement.

3.3.4.3. Unexpected harmonization

Many of the significant effects reported in § 3.3.3.2 above are most readily explained by examining the lexical items used in the experiment; specifically, the [ɒCæ] and [æCɑ] items frequently harmonized in an unexpected fashion. Table 13 shows the expected pronunciation based on the orthography, which was sometimes observed, as well as the commonly used harmonized pronunciation for each item. Notably, the opposite harmonizations never surfaced: [ɑfɑt], [gɑrɑp], [ʑæfæ], and [ʃɑrɑp] were not attested (though in the case of /ʑæfɑ/, many utterances featured two similar central vowels not clearly aligned with /ɑ/ or /æ/). The attested harmonizations were widespread and consistent across speakers, though some disharmonic utterances also appeared.

Table 13: [ɒCæ] and [æCɑ] lexical items in Tatar

Orthography-inspired phonological transcription	Gloss	Observed pronunciation	Unobserved pronunciation
/ɒfæt/	‘trouble, disaster’	[æfæt]	[ɑfɑt]
/gɒræp/	‘Arabic, Arab’	[gæræp]	[gɑrɑp]
/ʑæfɑ/	‘torment, suffering’	[ʑɑfɑ]	[ʑæfæ]
/ʃærɑb/	‘wine’	[ʃæræp]	[ʃɑrɑp]

While these unexpected harmonizations were consistent within each lexical item, they did not share any common pattern. Three items harmonized to the stressed final vowel, while one harmonized the stressed vowel to the unstressed vowel. Thus, while left-to-right harmony is expected in Tatar, three of the four items that underwent unexpected harmonization did so in an unexpected direction – right-to-left. This preference for right-to-left harmonization may be tied to Tatar stress and may represent an emerging tendency for speakers to repair disharmonic words through assimilation to the most prominent vowel, which is in the final, stressed syllable. Under this explanation, only one item, /ʃærɑb/, behaves in an unexpected fashion, adhering to the established pattern of Tatar harmony. This was also one of the two items for which harmonization was consistently applied, to the exclusion of an orthographic pronunciation (as shown in § 3.3.3.2.4); thus, it may belong to an older wave of harmonization than the other three items. (The other item that failed to show a difference in F2 across syllables, /ɒfæt/, had a highly skewed distribution of F2 values from its first syllable, necessitating the use of a non-parametric test. This skew should be taken as a reminder that while harmonization was frequent, it was not always present.) If /ʃærɑb/ indeed belongs to an older wave of harmonization, then the remaining three items, which all exhibited frequent harmonization to the stressed syllable, may represent an emerging pattern within Tatar phonology. Future investigations should consider whether this phenomenon is limited to a closed set of established loan words or whether it also applies to new loans – if possible, new loans from languages other than Russian that are less likely than Russian words to retain their original phonology among bilingual Russian-Tatar speakers.

One of the key shortcomings of the methodology used here is the inability to distinguish harmonized and coarticulated pronunciations. Indeed, asserting these as categories belies the reality reflected in the data – that vowel utterances in such words occupied a spectrum of acoustic values, from F2 values indistinguishable from the canonical standard, through minor coarticulation and notable assimilation to full harmonization. Future work on Tatar coarticulation should thus include a wider variety of target words, incorporate native speaker judgments on recorded items in order to identify fully harmonized utterances, and explore whether unexpected harmonization, observed here only intermittently and only in three items, represents a wider reorganization within Tatar phonology.

3.3.5. Conclusion

In this chapter, I have presented an original acoustic description of the Tatar vowel inventory. Two unique traits emerged: typologically unusual crowding near the central vowel space and increased variability in F2 for word-final high round vowels. These two trends are explained by reference to vowel harmony, which decreases the need for a strong front-back distinction outside the initial syllable. Central crowding also has historical roots in the Volga Vowel Shift, which centralized and lowered historically high vowels to create the modern Tatar mid vowel series.

In addition to this detailed acoustic description of Tatar vowels, this chapter explores the acoustics of vowel-to-vowel coarticulation in Tatar. Backness coarticulation in items containing [ɒCæ] and [æCɑ] sequences was difficult to evaluate due to unforeseen lexical effects, wherein unexpected harmonization led to frequent instances of complete assimilation between vowels. Coarticulation between /i/ and the two low vowels /æ/ and /ɑ/ was also examined, and robust patterns emerged in both F1 and F2 coarticulation. Anticipatory coarticulation was more widespread and of greater magnitude than carryover coarticulation, though coarticulatory effects in both directions were present. This finding provides initial support for the hypothesis that the strongest predictive factor of coarticulatory direction is the location of stress, which is word-final in Tatar and thus expected to trigger right-to-left coarticulation. Additional key findings related to consonant and vowel identity: /r/ was found to permit more (and greater) VV coarticulation across it than /f/, while the two target vowels /æ/ and /ɑ/ displayed affinities for different types of coarticulation. F1 effects were greater for /æ/, while F2 effects were greater for /ɑ/.

The predominance of anticipatory coarticulation in Tatar echoes the results from Beddor & Yavuz (1995) for Turkish, a language with similar patterns of harmony and stress. Furthermore, it contradicts the findings of Dye (2015) for Wolof and Pulaar, where the direction of coarticulation paralleled that of harmony regardless of the location of stress. The emerging polarization of coarticulation data from harmonization languages into these two parallel and opposing groups further reinforces how dangerous it is to draw cross-linguistic generalizations of the relationship between harmony and coarticulation. In the next chapter, I will explore the trends of VV coarticulation in Hungarian with the hope of bringing clarity to the many differing results found across languages.

4. HUNGARIAN

4.1. Introduction

Hungarian is a Uralic language with approximately 13 million speakers belonging to the Finno-Ugric language family (Eberhard, Simons, & Fennig, 2019). While it is chiefly spoken in Hungary, Hungarian-speaking communities also exist in Austria, Slovakia, Romania, the Ukraine, Croatia, Slovenia, and Serbia, as well as outside of Europe in the U.S. and Canada (Siptár & Törkenczy, 2000). As a language with left-to-right vowel harmony and word-initial stress, Hungarian is well-suited for this study because it presents a contrast to the left-to-right harmony and word-final stress of Tatar.

4.1.1. The vowels of Hungarian

The Hungarian language features fourteen vowel phonemes, seven short and seven long, as shown in Table 14. While vowel quantity is primarily distinguished phonetically via duration, as the name implied, the length distinction is accompanied by further phonetic differentiation for two of the seven pairs. The long counterpart of short /ɛ/ is raised to /e:/, and the short counterpart of long /ɑ:/ is rounded to /ɔ/, though the underlying vowel is argued to be unrounded (Vago, 1974).

Table 14: Hungarian vowel phonemes. (Data drawn from Siptár & Törkenczy, 2000 & Vago, 1974.)

	[-back][-round]		[-back][+ round]		[+back][- round]		[+back][+ round]	
	Short	Long	Short	Long	Short	Long	Short	Long
High	/i/	/i:/	/y/	/y:/			/u/	/u:/
Mid		/e:/	/ø/	/ø:/			/o/	/o:/
Low	/ɛ/					/ɑ:/	/ɔ/	

4.1.2. Vowel harmony in Hungarian

Hungarian vowel harmony is primarily backness harmony, though to a limited degree it also affects the feature [round]. As a stem-controlled system in a suffixing language, Hungarian harmony proceeds from left to right, altering the quality of affix vowels to agree with the final stem vowel. For the purposes of harmony, Hungarian vowels divide into three classes: the front vowels /y, y:, ø, ø:/, the back vowels /u, u:, o, o:, ɔ, a:/, and the neutral vowels /i, i:, ɛ, e:/. Neutral vowels can appear with either front vowels or back vowels and are transparent to harmony, meaning that they do not influence the selection of front or back vowels in affixes. Table 15 provides examples of the three main types of harmonic words.

Table 15: Examples of front, back, and mixed roots in Hungarian. Data drawn from Siptár & Törkenczy, 2000 & Vago, 1974. Forms with * have undergone a process of vowel lengthening that applies to low vowels in root-final open syllables when affixes are appended to the root.

	Root	Dative	Ablative	Gloss
Front Roots	/ty:z/	/ty:znɛk/	/ty:ztø:l/	'fire'
	/ørøm/	/ørømnɛk/	/ørømtø:l/	'joy'
	/tykør/	/tykørnɛk/	/tykørtø:l/	'mirror'
Back Roots	/hɑ:z/	/hɑ:znɔk/	/hɑ:zto:l/	'house'
	/vɑ:roʃ/	/vɑ:roʃnɔk/	/vɑ:roʃto:l/	'city'
	/mo:kuʃ/	/mo:kuʃnɔk/	/mo:kuʃto:l/	'squirrel'
Mixed Roots	/bikɔ/	/bikɑ:nɔk/*	/bikɑ:to:l/*	'bull'
	/rɔdi:r/	/rɔdi:rnɔk/	/rɔdi:rto:l/	'eraser'
	/be:kɔ/	/be:kɑ:nɔk/*	/be:kɑ:to:l/*	'frog'

4.1.2.1. Neutral vowels in Hungarian

While mixed roots containing both back vowels and neutral vowels always take back affixes, there are also a number of Hungarian roots that contain only neutral vowels. The affix selection of these roots is lexically specified and cannot be predicted from the phonology of the lexeme. Table 16 gives examples of neutral roots that take back and front vowel affixes.

Table 16: Examples of neutral roots in Hungarian. Data from Vago (1974).

	Root	Dative	Ablative	Gloss
Neutral Roots with Front Affixes	/si:n/	/si:nnɛk/	/si:ntø:l/	'color'
	/sɛge:ni/	/sɛge:ninɛk/	/sɛge:nitø:l/	'poor'
	/kɛrt/	/kɛrtnɛk/	/kɛrttø:l /	'garden'
Neutral Roots with Back Affixes	/hi:d/	/hi:dnɔk/	/hi:dto:l/	'bridge'
	/ɲi:l/	/ɲi:lnɔk/	/ɲi:lto:l/	'arrow'
	/tse:l/	/tse:lnɔk/	/tse:lto:l/	'aim'

While neutral vowels surface as phonetically front, differences in articulation have been detected according to the harmonic class of the root even when no affix is present to induce coarticulation. Benus & Gafos (2007) used ultrasound and electromagnetic midsagittal articulometry to chart the exact tongue position of three Hungarian speakers as they produced near-minimal pairs of neutral roots, where one member of the pair took a back affix (termed anti-harmonic) and the other a front (harmonic) affix. They found that even when the root was in its simplest form, with no affix present, measurable differences in articulation were present: the tongue body was more retracted in neutral roots that took back vowel affixes than those that took front affixes. This sub-phonemic distinction depended entirely on the speaker's knowledge of the root's class, since the distinction occurred even in the bare root when no affixal vowel was present to trigger coarticulation. The authors attribute the development of neutral vowels in harmonizing languages to the quantal acoustic nature of vowels in the upper front region of the vowel space, which tend to allow a great deal of articulatory retraction with little to no perceptual effect. A later study of anti-harmonic stems in Hungarian found no trace of these articulatory differentiations in the acoustics (Blaho & Szeredi, 2013); thus, the phenomenon is not expected to interfere with the acoustic analysis of harmony pursued in this chapter.

4.1.2.2. Rounding harmony

Hungarian rounding harmony is extremely restricted; stem-internal phonotactic restrictions do not require stem vowels to agree in rounding, and most affixes do not possess rounded and unrounded variants. The exception is affixes that allow short mid vowels, which exhibit a three-way distinction between /ɛ/, /ø/, and /o/. For such affixes, affix selection depends on the backness of the root and the roundness of the final stem vowel. Thus, the suffix /-hOz/ 'to' surfaces as either /-hoz/, /-høz/, or /-hɛz/ according to the rounding and backness specification of the root vowel, as shown in (3).

(3) /tyzhøz/ 'to fire'
/vi:zhɛz/ 'to water'
/hɑ:zhoz/ 'to house'
Data drawn from Siptár & Törkenczy (2000)

Some exceptions to this pattern, linked to a separate phonological lowering process, are discussed in Siptár & Törkenczy (2000, pp. 224-230).

4.1.3. Stress in Hungarian

Word-level stress in Hungarian falls on the initial syllable and is distinguished by pitch contours reinforced by changes in intensity (Siptár & Törkenczy, 2000). While some sources have argued for an alternating secondary stress (Kager, 1995; see also summary in Kerek, 1971), Siptár & Törkenczy (2000) assert that such regular secondary stresses do not align with native intuitions. Furthermore, in some sentences, the syntax is capable of removing primary stress and appending words enclitically to the previous word, resulting in stresslessness (Siptár & Törkenczy, 2000). In this chapter, target words are embedded in syntactic environments that do not affect their naturally occurring stress patterns, and only disyllabic stimuli are examined, eliminating the need to address the question of secondary stress. All target words carry only the expected initial stress.

4.1.4. Coarticulation in Hungarian

In addition to examining bare stems containing neutral vowels affiliated with front and back suffixes, Benus & Gafos (2007) also examined the articulation of neutral vowels in minimal pairs differing in backness, as shown in (4).

(4)	zefírben	zafírban
	[zefiːrbɛn]	[zɔfiːrbɔn]
	'zephyr'	'sapphire'

Data from Benus & Gafos (2007), p. 276.

Benus & Gafos observed retraction in back vowel contexts for all four neutral vowels /i, iː, ɛ, eː/ However, it is not clear whether this retraction should be attributed to vowel-to-vowel coarticulation, an underlying lexical effect as described for bare stems in § 4.1.2.1 above based on data from the same study, or a combination of both. Studies of coarticulation in Hungarian have typically focused on the neutral vowels; to my knowledge, the current study is the first to document acoustic VV coarticulation in a non-neutral Hungarian vowel (namely, /ɔ/).

4.1.5. Hypothesis

In the Tatar study, I explored theories predicting the prevailing direction of coarticulation in harmonizing languages, which led to contrasting predictions for Tatar. By applying the same lines of reasoning to Hungarian, which shares a similar pattern of palatal harmony with Tatar, but features initial rather than final stress, both hypotheses predict coarticulation in a single direction. Since stress falls on the initial syllable of each Hungarian target word, depending on stress as a predictor of coarticulation leads to the expectation that carryover coarticulation will be preferred. Similarly, if there is synchronic pressure to maintain a parallel between the directions of harmony and coarticulation, this pressure will reinforce the preference for carryover coarticulation in order to match Hungarian's left-to-right pattern of harmony.

Hypothesis 5: If stress is the strongest predictor of coarticulatory direction, carryover coarticulation is expected to outweigh anticipatory in Hungarian in order to preserve word-initial stressed vowels as the best triggers and poorest targets of coarticulation.

Hypothesis 6: If maintaining a directional parallel between vowel harmony and coarticulation is a controlling factor in determining coarticulatory direction, carryover coarticulation is expected to outweigh anticipatory coarticulation in Hungarian in order to match the left-to-right direction of harmony.

4.2. Methods

4.2.1. Participants

Twenty-two native speakers of Hungarian completed a sentence reading task in a sound-insulated booth in Budapest, Hungary. Data from two speakers was excluded for early bilingualism and significant time spent outside Hungary during adolescence. Of the remaining twenty speakers whose data was analyzed, thirteen were female and seven were male. Participants ranged in age from 18 to 45 years (M = 27.5; SD = 8.5). All participants had some experience in at least one foreign language; fourteen evaluated their English by self-report as "good" or better (4 on a 7-point Likert scale), and five evaluated their German at or above this level. Only one participant reported proficiency in any other language as "good," though many were familiar with other languages, including Spanish, Italian, Russian, French, and Japanese. All participants had resided primarily in Hungary; only two had spent more than a year outside of Hungary.

4.2.2. Stimuli

Forty disyllabic target words were recorded; all target words shared the form (C)VCV, where each vowel was either /ɔ/, /ɛ/, or /i/, intervening consonants were /f/, /k/, or /p/, and initial consonants, when present, were /k/ or /t/. Because Hungarian stress is word-initial, the most prominent syllable was always the first syllable. Target words were chosen to create minimal sets allowing comparison of the canonical /ɔCɔ/ and /ɛCɛ/ forms without alteration for lexical gaps, using /ɔ/ and /ɛ/ as target vowels and /ɔ/, /ɛ/, and /i/ as trigger vowels. Thus, ten of the target words were real Hungarian lexical items and thirty were non-words. (See **Error! Not a valid bookmark self-reference.** for a summary of all Hungarian target words.) Three carrier phrases were randomized to interrupt the monotony of the task and prevent participants from developing a list intonation across phrases. The three carrier phrases, shown in Appendix B, all shared a similar syntactic structure and identical phonological context immediately following and preceding the embedded target word. Each target word appeared in each carrier phrase once for every participant, resulting in three repetitions of each target word per participant.

Table 17: Hungarian target words

Hungarian	Gloss
afa	*non-word*
afe	*non-word*
afi	*non-word*
aka	*non-word*
ake	*non-word*
aki	who
apa	father
ape	*non-word*
api	*non-word*
efa	*non-word*
efe	*non-word*
efi	*non-word*
eka	*non-word*
eke	plough
eki	*non-word*
epa	*non-word*
epe	gall
epi	*non-word*
ifa	a type of vehicle
ife	*non-word*
ika	*non-word*

Table 17 continued

ike	*non-word*
ipa	a type of beer
ipe	*non-word*
kapa	hoe
kape	*non-word*
kapi	*non-word*
kepa	*non-word*
kepe	*non-word*
kepi	*non-word*
kipa	a religious cap
kipe	*non-word*
taka	*non-word*
take	*non-word*
taki	*non-word*
teka	*non-word*
teke	bowl
teki	nickname for turtle
tika	*non-word*
tike	*non-word*

4.2.3. Procedure

In addition to the sentence reading task, participants completed a language background questionnaire focused on their early language exposure, knowledge of languages other than Hungarian, and Hungarian and foreign language proficiency. Recordings were taken using a DPA 4066 omnidirectional head-mounted microphone attached to an M-Audio NRV10 analog mixer. The sentence reading task was conducted in Speech Recorder (Draxler & Jänsch, 2004), which presented sentences in black font on a white screen. The task was self-paced, and breaks were offered every forty sentences. As in the Spanish and Tatar studies, all participants received compensation for their time.

4.2.4. Measurements

Identically to the Tatar and Spanish studies, recorded data were digitized at 44.1 kHz and target vowels annotated in Praat v. 6.0.23 (Boersma & Weenink, 2017). F1 and F2 were extracted using Praat's Burg LPC algorithm at 50% and 90% of the vowel for V_1 and at 10% and 50% of the vowel for V_2; extracted formant values were reviewed visually by a researcher and subjected to hand correction when needed. Normalization was completed through the log-additive regression procedure (Barreda & Nearey, 2017) in R (R Core Team, 2017) described in § 2.2.4.

4.2.5. Analysis

As in previous chapters, linear mixed models were run to detect coarticulation and evaluate its magnitude. Four models took normalized F1 or F2 as their dependent variable, examining measurements made at vowel edge (two models) and midpoint (two models). The F1 models examined height coarticulation, while the F2 models examined coarticulation in backness and rounding combined. In these models, a random factor of Subject was included as well as the four independent factors Consonant (/k/ versus /p/ versus /f/), Direction (Anticipatory versus Carryover), Target (/ɛ/ versus /ɔ/), and Trigger (/ɛ/ versus /ɔ/ versus /i/). Because the dataset consisted of disyllabic stimuli, the two levels of Direction could equally have been labeled Syllable: coarticulation in V_1 was anticipatory, while coarticulation in V_2 was carryover. Interactions between Target and Trigger; Consonant, Target, and Trigger; Direction, Target, and Trigger; and Consonant, Direction, Target, and Trigger were also included. In these models, the presence of significant coarticulation was judged by the main effect of Trigger, estimating coarticulation throughout the dataset, and the significance of pairwise comparisons between levels of Trigger (specifically, between the canonical and coarticulated target word types) in each condition of Target, Consonant, and Direction, evaluating coarticulation in specific conditions. Two additional models took F2 and F1 difference scores as a dependent variable. Difference scores were calculated for each observation by subtracting the observed F1 or F2 value from the canonical mean for the relevant vowel and participant. This calculation aimed to encode change in the coarticulatory direction as positive and the dissimilatory direction as negative, with the understanding that F2 was lowest for /ɔ/, then /ɛ/ and finally /i/, while F1 was lowest for /i/, followed by /ɔ/ and then /ɛ/. (For four speakers, the canonical F1 mean of /ɔ/ was higher than for /ɛ/; appropriate adjustments were made to the sign of the affected difference scores for these speakers.) Due to the higher number of factors involved in these models, each one was fit to the data individually to achieve the best possible model, incorporating the random factors Subject and Item and independent variables Target, Trigger, Consonant, and Direction, as well as Time Point (Midpoint versus Edge). The final models are represented in full in Appendix C, selected results are presented in § 4.3.2.3 and § 4.3.3.3, and the code for each model is provided in Appendix D. SPSS v. 24.0 (IBM Corp, 2016) or v. 25.0 (IBM Corp, 2017) was used to carry out all models.

4.3. Results

4.3.1. Real words versus non-words

In order to evaluate the impact of mixing real words and non-words in the target word set, a preliminary analysis was run using Lexical Status (Real versus Non-word) as a factor. While the effect of Lexical Status on coarticulation could doubtless provide fodder for multiple studies all on its own, it is not the primary focus of this dissertation, and the present study was not designed for the purpose of evaluating the impact of Lexical Status on coarticulatory patterns. This preliminary analysis aimed to justify combining real and non-words together in the main analysis, and it focused on magnitude of coarticulation. This focus was chosen in order to avoid interference arising from the imbalanced distribution of real and non-words across levels of Consonant, Direction, Target, and Trigger in the dataset, which was deemed more likely to give rise to misleading results if separate analyses were run on real and non-word subsets of the data. No significant main effects or interactions with Lexical Status emerged in this analysis with regard to either F1 or F2. Therefore, in the main analysis reported below, real words and non-words were analyzed together, with no separation between groups or special attention given to lexical status beyond this preliminary analysis.

4.3.2. Height coarticulation

4.3.2.1. At vowel edge

The model evaluating the presence or absence of statistically significant VV coarticulation in F1 at vowel edge used normalized F1 as its dependent variable in order to examine coarticulation in height. The model evaluated coarticulation through the main effect of Trigger, providing a measure of coarticulation in various conditions through the pairwise comparisons of Trigger – that is, by comparing coarticulated target words (such as /ɔkɛ/) to their canonical counterparts (like /ɔkɔ/). (Comparisons of two coarticulated words, such as /ɔkɛ/ and

/ɔki/, are not reported.) Each of the main effects was significant: Target ($F(1, 3487.059) = 140.611$, $p < .001$), Trigger ($F(2, 3487.032) = 25.717$, $p < .001$), Consonant ($F(2, 3487.037) = 214.325$, $p < .001$), and Direction ($F(1, 3487.051) = 6.592$, $p = .010$). Examining the main effect of Target showed that /ε/ had a higher F1 (M = -0.455), indicating a lower articulation, than /ɔ/ (M = -0.523). The main effect of Trigger pointed to global coarticulation: vowels were lowest (with the highest F1) when preceded or followed by /ɔ/ (M = -0.478) or /ε/ (M = -0.471), and highest (lowest F1) when near /i/ (M = -0.518). The effect of Consonant highlighted how CV coarticulation differed across all three groups, with the highest F1 alongside /f/ (M = -0.437), followed by /p/ (M = -0.463) and then /k/ (M = -0.567). Finally, the results for Direction indicated that first-syllable vowels (those measured for anticipatory coarticulation) had a higher F1 (M = -0.482) than second-syllable vowels (M = -0.496). Since stress is realized through pitch contours and changes to pitch entail changes to formants, some differentiation across syllables is expected and this main effect is not expected to reflect directional differences. Instead, directional differences in coarticulation are explored through the interactions involving both Direction and Trigger.

In addition to these main effects, four significant interactions were included in the model. The significant interaction between Target and Trigger ($F(2, 3487.036) = 5.399$, $p = .001$)

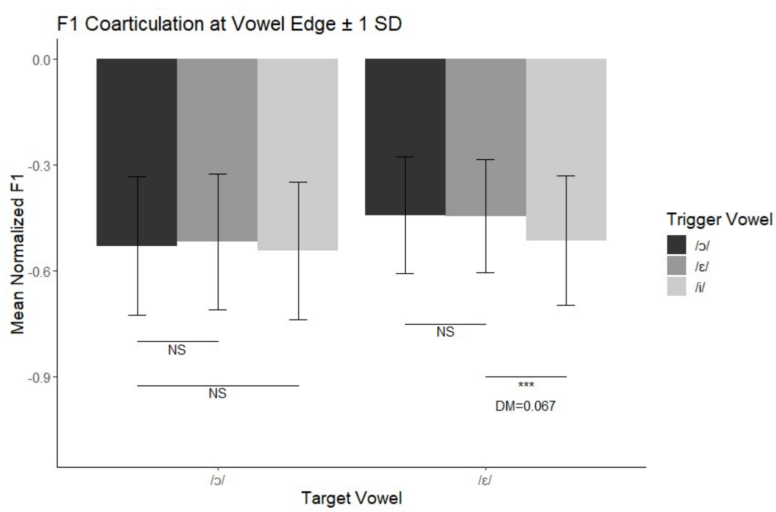

Figure 29: Target Vowel by Trigger Vowel interaction in F1 at vowel edge in Hungarian. Shorter bars indicate lower vowels. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates p < .001, ** indicates p < .01, and * indicates p < .05. DM denotes "difference in means."

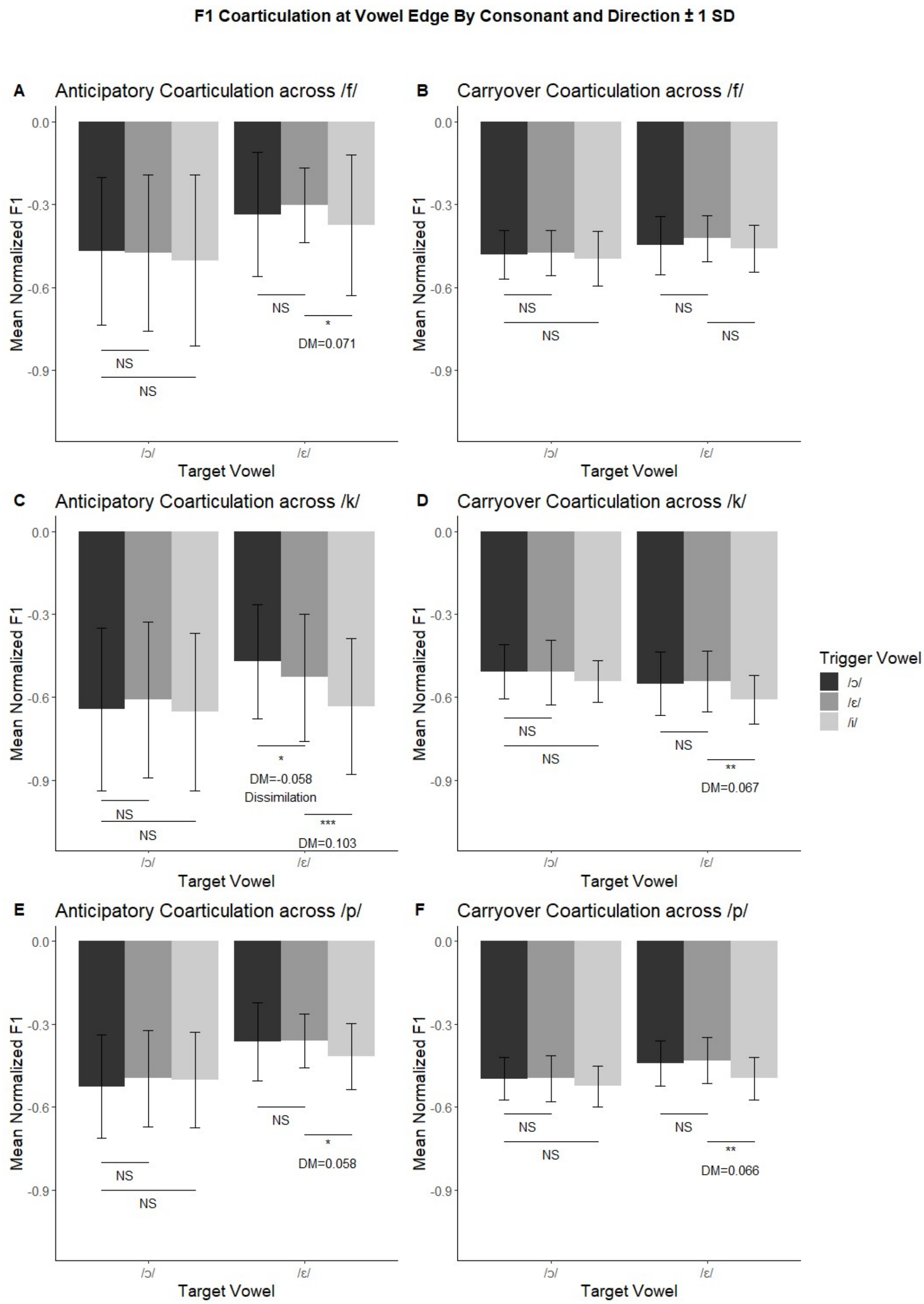

Figure 30: Effect of Trigger Vowels /ɔ/, /ɛ/, and /i/ on Target Vowels /ɔ/ and /ɛ/ across /f/, /k/, and /p/ on F1 in the anticipatory and carryover directions at vowel edge in Hungarian. Shorter bars indicate lower vowels. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$. DM denotes "difference in means."

showed that the magnitude of coarticulation differed across target-trigger pairs: pairwise comparisons between the levels of Trigger for each Target found a significant difference across the canonical and coarticulated conditions only for target /ɛ/ and trigger /i/. All other target-trigger pairings were not significant, indicating that statistically detectable VV coarticulation with regard to height was not present in the acoustics. (See Figure 29.)

Additionally, the three-way interactions between Consonant, Target, and Trigger ($F(10, 3487.046) = 5.399$, $p < .001$) and Direction, Target, and Trigger ($F(5, 3487.047) = 18.691$) $p < .001$) and the four-way interaction between Consonant, Direction, Target, and Trigger ($F(12, 3487.041) = 6.831$, $p < .001$) were all significant, with pairwise comparisons identifying significant coarticulation, as shown in Figure 30. As can be seen, pairwise comparisons found significant assimilation only for target /ɛ/, most often triggered by /i/, more often with /k/ than /f/ or /p/, and more often in the anticipatory direction than the carryover, though both were attested. Thus, height coarticulation was limited to the target /ɛ/ - trigger /i/ pair, but was distributed across several conditions of Direction and Consonant.

4.3.2.2. At vowel midpoint

The main effects of Target ($F(1, 3676.149) = 73.194$, $p < .001$), Consonant ($F(2, 3676.148) = 11.243$, $p < .001$), and Direction ($F(1, 3676.147) = 1035.525$, $p < .001$) were significant in the F1 model at vowel midpoint. Just as in the vowel edge model, /ɛ/ still had a lower articulation ($M = -0.359$) than /ɔ/ ($M = -0.387$), /f/ still abutted the vowels with the highest F1 ($M = -0.362$), followed by /p/ ($M = -0.374$) and then /k/ ($M = -0.383$), and first-syllable vowels (anticipatory condition) still had a higher F1 ($M = -0.320$) than second-syllable vowels (carryover condition; $M = -0.426$).

The F1 midpoint model differed from the edge model when it came to the main effect of Trigger, which was not significant ($F(2, 3676.146) = 2.019$, $p = .133$). This suggests that on the whole, VV coarticulation in height did not extend to vowel midpoint, since no statistically detectable difference existed between the levels of Trigger. As might be expected, given this general lack of coarticulation, the interactions between Target and Trigger ($F(2, 3676.153) = 1.032$, $p = .356$) and Consonant, Target, and Trigger ($F(10, 3676.150) = 1.575$, $p = .107$) were not significant. However, the interactions between Direction, Target, and Trigger ($F(5, 3676.151) = 4.339$, $p = .001$) and Direction, Consonant, Target, and Trigger ($F(12,$

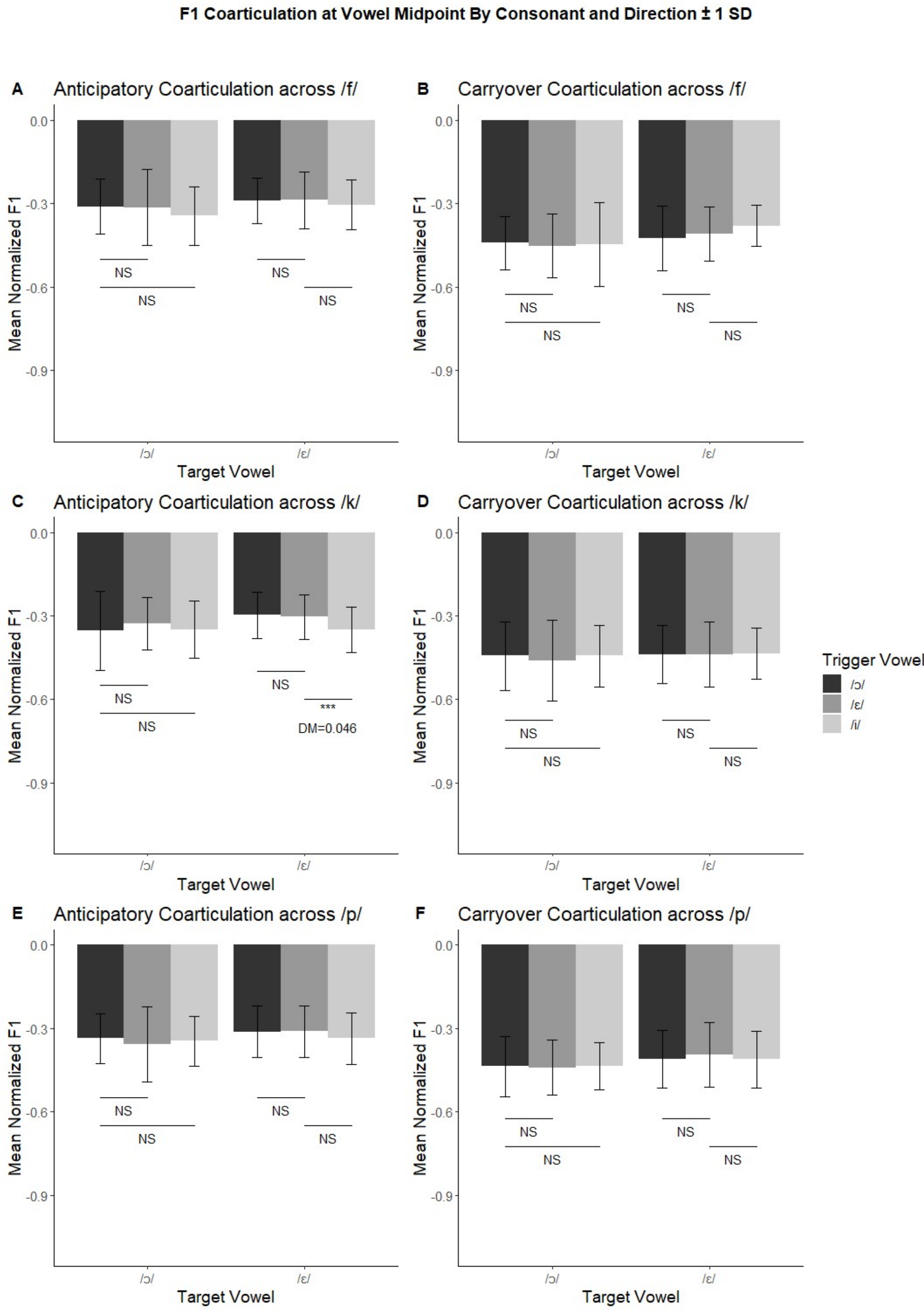

Figure 31: Effect of Trigger Vowels /ɔ/, /ɛ/, and /i/ on Target Vowels /ɔ/ and /ɛ/ across /f/, /k/, and /p/ on F1 in the anticipatory and carryover directions at vowel midpoint in Hungarian. Shorter bars indicate lower vowels. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates p < .001; **, p < .01; and *, p < .05. DM denotes “difference in means.”

3676.147) = 2.613, p = .002) were significant, indicating that coarticulation might indeed persist to midpoint under some, though not many, conditions. Figure 31 displays the effect of Trigger under each combination of Target, Trigger, Direction, and Consonant to reveal which contained significant coarticulation. As can be seen, the only condition in which coarticulation was significant was in the anticipatory direction across /k/ between target /ɛ/ and trigger /i/. Under no other conditions was anticipatory coarticulation statistically detectable at vowel midpoint.

4.3.2.3. F1 magnitude model

A third model analyzed F1 difference scores as a dependent variable intended to quantify magnitude of coarticulation. Difference scores were calculated from each subject's canonical mean for the target vowel in question, such that positive scores represented shifts in the coarticulatory direction from the mean. (See § 2.2.5.2.) Negative scores should not be automatically interpreted as dissimilatory, however, since the mean represents an average across many consonantal environments as well as time points. This magnitude model had five independent factors: Target (/ɛ/ versus /ɔ/), Trigger (/ɛ/ versus /ɔ/ versus /i/), Direction (Anticipatory versus Carryover), Consonant (/f/ versus /k/ versus /p/), and Time Point (Edge versus Midpoint), as well as numerous interactions and random factors for Subject and Item. The full complement of interactions included in the final, best-fitting model is reported in Appendix C.

Five key findings emerged from the magnitude model. The first related to Target, which did not yield a significant main effect ($F(1, 29.895) = 1.751$, $p = .196$), indicating that the magnitude of coarticulation found across the two targets /ɛ/ and /ɔ/ did not differ appreciably. However, the Target by Trigger interaction was significant ($F(2, 15.501) = 8.304$, $p = .004$), showing that the magnitude of coarticulation depended on both target and trigger vowel identity. Post-hoc pairwise comparisons revealed that trigger /i/ induced greater coarticulation ($M = 0.032$) than /ɔ/ ($M = 0.003$; $p < .001$) or the canonical condition ($M = -0.003$; $p < .001$) in target /ɛ/, while coarticulation was relatively steady (no significant differences) across triggers (including the canonical condition) for target /ɔ/. This reflected the results of the vowel edge model, which found that significant coarticulation collapsed across Consonant and Direction was present only for the trigger /i/ - target /ɛ/ pair, just as in the non-magnitude models.

The main effects of Trigger ($F(2, 23.273) = 9.540$, $p = .001$), Direction ($F(1, 197.223) = 37.417$, $p < .001$), Consonant ($F(2, 13.944) = 54.259$, $p < .001$), and Time Point ($F(1, 7171.123) = 384.265$, $p < .001$) were also significant. The significant effect of Trigger pointed to widespread VV coarticulation; its pairwise comparisons demonstrated that /i/ induced greater coarticulation (M = 0.020) than /ɛ/ (M = 0.004; p = .012) or /ɔ/ (M = 0.000; p = .001). With regard to Direction, carryover effects (M = 0.019) had a greater magnitude than anticipatory ones (M = -0.003), and with regard to Consonant, the greatest coarticulation accompanied intervening /k/ (M = 0.037), surpassing both /f/ (M = -0.011; p < .001) and /p/ (M = -0.001; p < .001). (No significant difference existed between /f/ and /p/.) Finally, pairwise comparisons related to Time Point demonstrated that coarticulation was greater at vowel edge (M = 0.042) than at midpoint (M = -0.026); the vowel-to-vowel effect wore off with increased temporal separation, exactly as expected. Thus, height coarticulation possessed greater magnitude between /ɛ/ and /i/ compared to other vowel pairs, in the carryover direction than the anticipatory, across /k/ rather than /f/ or /p/, and at vowel edge over midpoint.

4.3.3. Backness coarticulation

4.3.3.1. At vowel edge

To evaluate coarticulation in backness and rounding between /i/, /ɛ/, and /ɔ/, models were run with normalized F2 as the dependent variable; this section reports the results of the F2 model for measurements taken at vowel edge. In this model, F2 measurements were significantly impacted by target vowel identity, VV coarticulation, CV coarticulation, and syllable number, reflected by significant main effects of Target ($F(1, 3487.048) = 23806.853$, $p < .001$), Trigger ($F(2, 3487.024) = 218.424$, $p < .001$), Consonant ($F(2, 3487.029) = 1662.665$, $p < .001$), and Direction ($F(1, 3487.041) = 6.312$, $p = .012$).

The significant main effect of Target indicated that the target vowels /ɛ/ and /ɔ/ were indeed differentiated by F2 as expected. The higher F2 of /ɛ/ (M = 0.681) shows that this vowel occupies a more fronted position in the vowel space than /ɔ/ (M = 0.207). By contrast, the significant main effect of Trigger pointed to VV coarticulation, wherein vowels neighboring /i/ were most fronted (M = 0.484), those near /ɛ/ somewhat less so (M = 0.443) and those near /ɔ/ were most retracted (M = 0.405). Similarly, the significant effect of Consonant pointed to CV coarticulation. The most fronted vowels abutted /k/ (M = 0.554), followed by /f/ (M = 0.406) and then /p/ (M = 0.373). Finally, the effect of Direction corresponded to acoustic differences across syllables, since carryover coarticulation was always measured on V_2 and anticipatory on V_1. (Coarticulation by direction was analyzed through interactions between Direction and Trigger.) In general, first-syllable vowels (anticipatory condition; M = 0.448) were slightly more fronted than second-syllable vowels (carryover condition; M = 0.440). This difference is attributed to the effect of stress and, possibly, imbalances between front and back target vowels in each syllable across the dataset.

While coarticulation was generally present, judging by the main effect of Trigger, the magnitude of coarticulation did not differ across target vowels, as shown by the lack of a significant interaction between Target and Trigger ($F(2, 3487.028) = 1.907$, $p = .149$). However, the presence of coarticulation did vary across conditions of Consonant and Direction, as attested by significant interactions between Consonant, Target, and Trigger ($F(10, 3487.037) = 12.741$, $p < .001$), Direction, Target, and Trigger ($F(5, 3487.038) = 20.805$, $p < .001$), and Consonant, Direction, Target, and Trigger ($F(12, 3487.033) = 5.638$, $p < .001$). Figure 32 shows the means, standard deviations, and results of pairwise comparisons between canonical and coarticulated conditions for each combination of Direction and Consonant, focusing on comparisons evaluating the significance of differences between canonical and non-canonical levels of Trigger. Coarticulation is present in all but two conditions (carryover across /k/ or /f/ with trigger /ɛ/) for target /ɔ/ and in seven out of twelve conditions for target /ɛ/. Coarticulation in /ɛ/ is lacking across /f/ more frequently than /k/ or /p/, in the carryover direction more often than the anticipatory, and only with trigger /ɔ/. (Trigger /i/ always induced significant coarticulation in this model.) Thus, backness coarticulation occurred in both directions across many combinations of Target, Trigger, and Consonant at vowel edge.

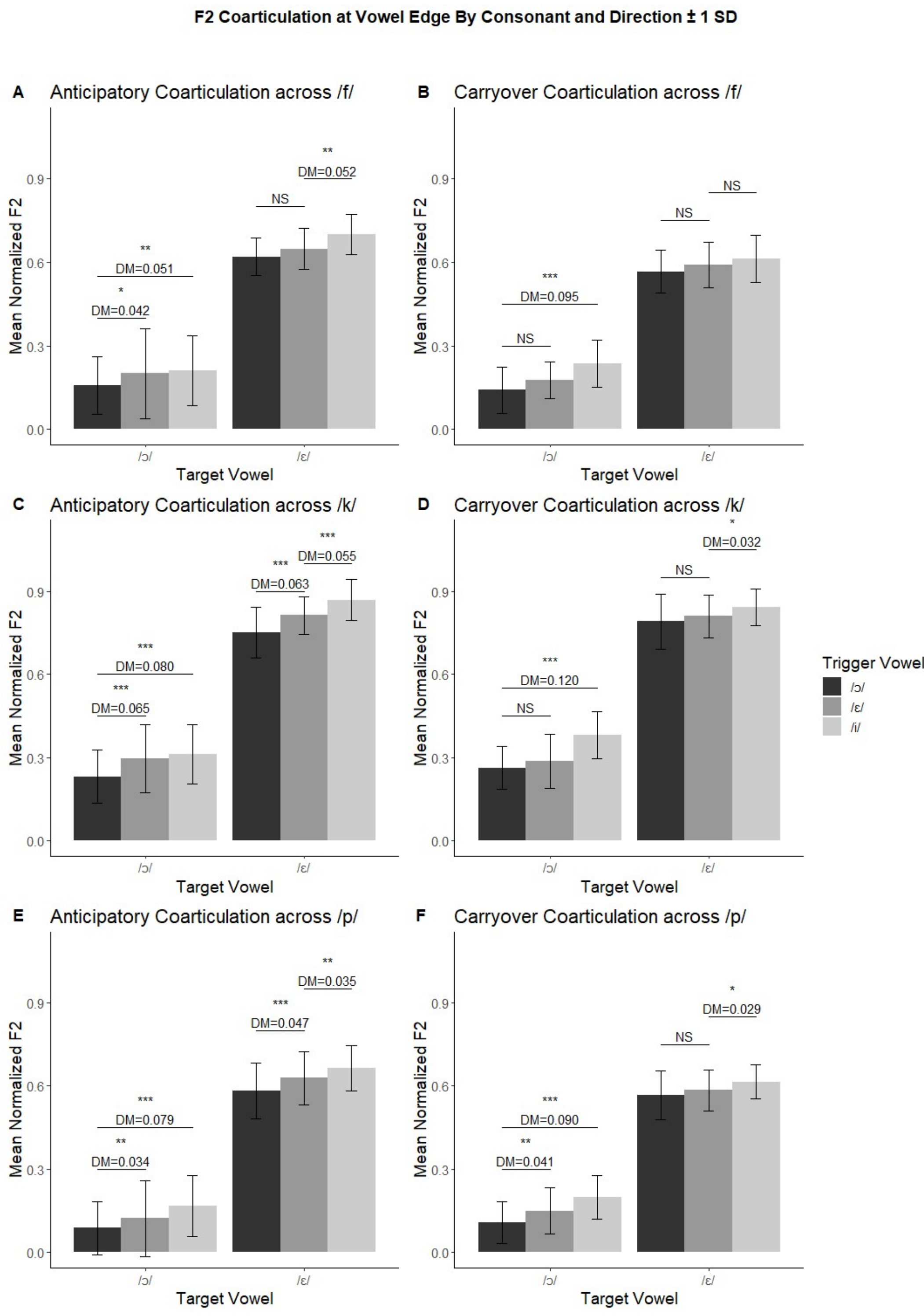

Figure 32: Effect of Trigger Vowels /ɔ/, /ɛ/, and /i/ on Target Vowels /ɔ/ and /ɛ/ across /f/, /k/, and /p/ on F2 in the anticipatory and carryover directions at vowel edge in Hungarian. Shorter bars indicate backer vowels. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates p < .001; **, p < .01; and *, p < .05. DM denotes "difference in means."

4.3.3.2. At vowel midpoint

A similar model was run on F2 at vowel midpoint to detect under which conditions VV coarticulatory effects remained statistically significant until the center of the vowel. On the whole, the main effects mirrored those found in the edge model, with significant effects for Target (F(1, 3676.047) = 20637.786, p < .001), Trigger (F(2, 3676.044) = 47.943, p < .001), Consonant (F(2, 3676.046) = 323.818, p < .001), and Direction (F(1, 3676.044) = 4.241, p = .040).

The results for Target showed that /ɔ/ (M = 0.260) was indeed backer than /ɛ/ (M = 0.690), reflecting the basic expectations associated with the arrangement of the vowel space. The significant main effect of Trigger demonstrated that VV coarticulation was widespread, with trigger /i/ (M = 0.495) fronting its targets more than either /ɛ/ (M = 0.470, p < .001) or /ɔ/ (M = 0.460, p < .001) and /ɛ/ fronting its targets more than /ɔ/ (p = .030). Details of the effect of Consonant were tied to CV coarticulation: vowels abutting /k/ were significantly more fronted (M = 0.524, p < .001) than those near /p/ (M = 0.452) or /f/ (M = 0.448). (Unlike at vowel edge, no significant difference existed between vowels next to /p/ and those by /f/.) Finally, the main effect of Direction showed how first-syllable (anticipatory) vowels were slightly less back (M = 0.478) than second-syllable vowels (M = 0.472).

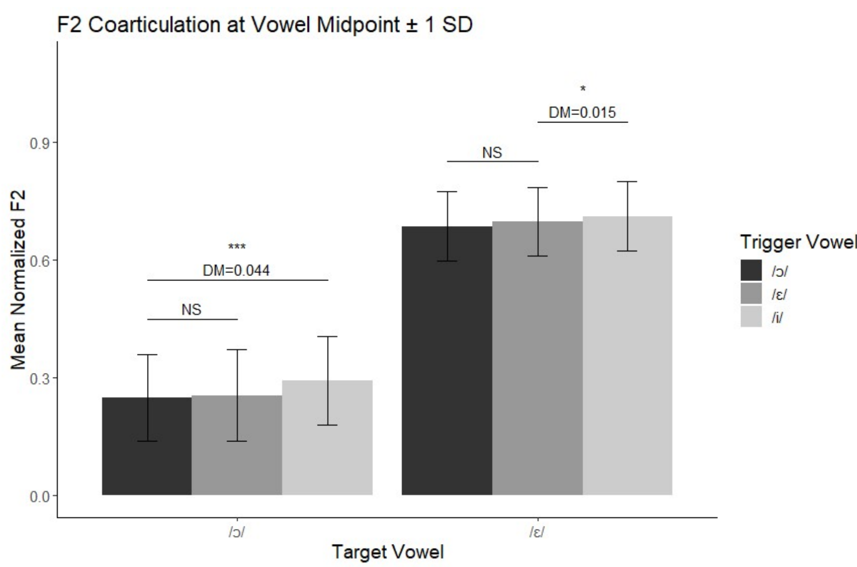

Figure 33: Target Vowel by Trigger Vowel interaction in F2 at vowel midpoint in Hungarian. Shorter bars indicate backer vowels. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates p < .001; **, p < .01; and *, p < .05. DM denotes “difference in means.”

In another reversal from the vowel edge model, the interaction between Target and Trigger was significant ($F(2, 3676.053) = 5.200$, $p = .006$), showing that the magnitude of coarticulation differed across target vowels. The results of pairwise comparisons are shown in Figure 33: as can be seen, only coarticulation triggered by /i/ was present; effects between /ɛ/ and /ɔ/ were not significant.

As in the other models, effects denoting changes in coarticulation across conditions of Consonant and Direction were all significant ($F(10, 3676.048) = 2.132$, $p = .019$ for Consonant by Target by Trigger; $F(5, 3676.051) = 36.482$, $p < .001$ for Direction by Target by Trigger; $F(12, 3676.044) = 5.333$, $p < .001$ for Consonant by Direction by Target by Trigger). The results of pairwise comparisons between the canonical and coarticulated conditions (that is, the comparisons directly analyzing VV coarticulation) for each level of Target and each combination of Consonant and Direction are displayed in Figure 34. Only coarticulation induced by trigger /i/ remained significant at vowel midpoint, and its occurrences were divided close to evenly across directions and consonants.

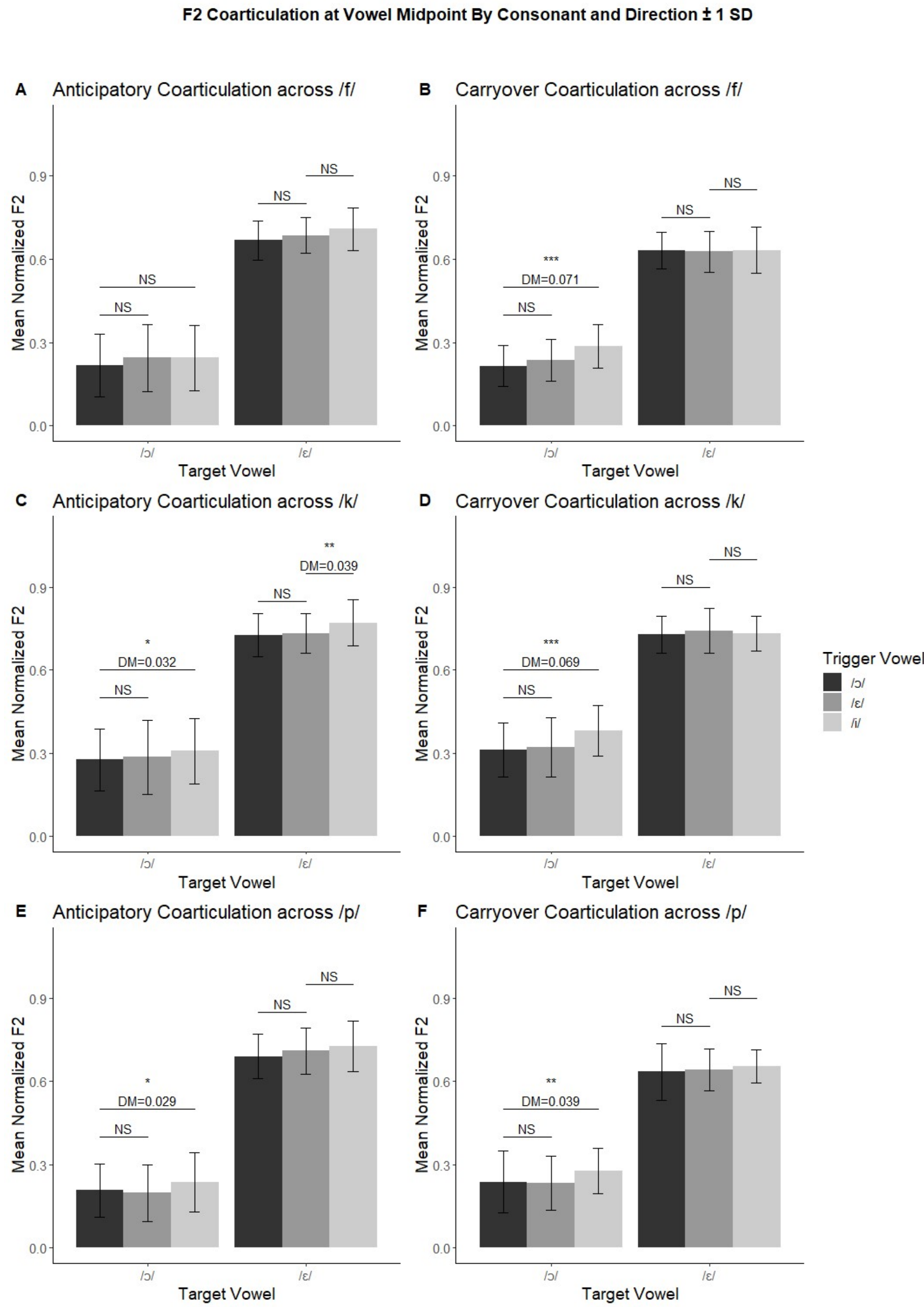

Figure 34: Effect of Trigger Vowels /ɔ/, /ɛ/, and /i/ on Target Vowels /ɔ/ and /ɛ/ across /f/, /k/, and /p/ on F2 in the anticipatory and carryover directions at vowel midpoint in Hungarian. Shorter bars indicate backer vowels. The difference between bars shows the average magnitude of coarticulation. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$; **, $p < .01$; and *, $p < .05$. DM denotes "difference in means."

4.3.3.3. F2 magnitude model

The edge and midpoint models indicated that F2 coarticulation was present in many conditions for all target-trigger combinations, but with no clear overwhelming directional or consonantal preferences (though coarticulation triggered by /i/ was most likely to remain statistically detectable at vowel midpoint). The F2 magnitude model sought to refine these findings by analyzing the magnitude rather than the presence of coarticulation, encapsulated in F2 difference scores. (See § 2.2.5.2 for more on the calculation of difference scores.) This model included random intercepts for Subject and Item, five independent factors (Target, Trigger, Direction, Consonant, and Time Point, with the same levels as in the F1 magnitude model), and several interactions. (See Appendix C for full summary.) The main effects of Target and Direction were not significant ($F(1, 16.987) = 3.626$, $p = .074$ for Target; $F(1, 24.959) = 0.060$, $p = .809$ for Direction), indicating no global trends in changes to the magnitude of coarticulation due to these factors. However, the interaction between Target and Direction was significant ($F(1, 16.985) = 17.602$, $p = .001$), and the relationship between magnitude of coarticulation and Direction was reversed by Target. Figure 35 displays the magnitude of coarticulation by Target

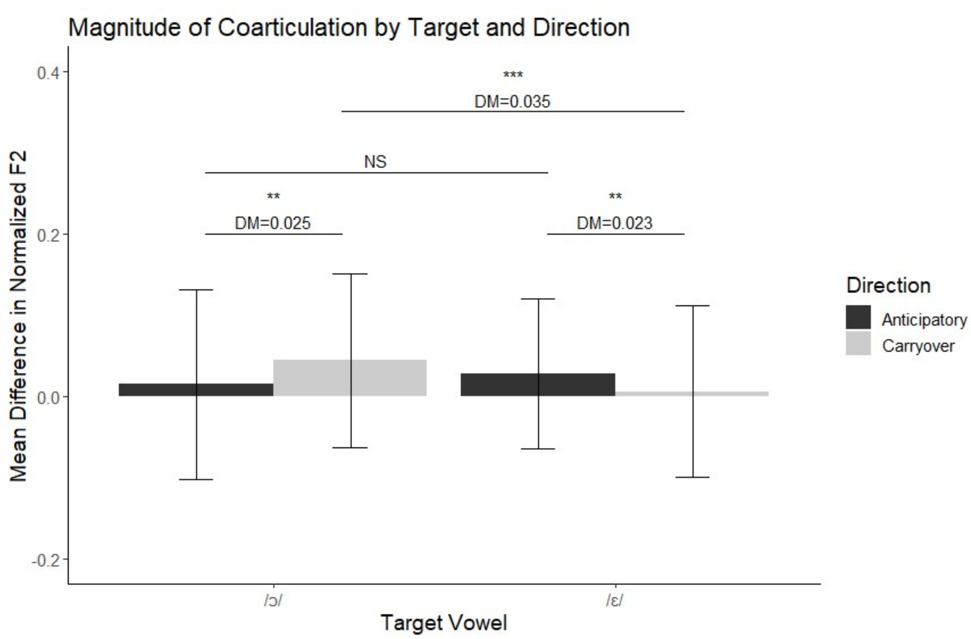

Figure 35: Magnitude of coarticulation, given in mean F2 difference scores, by Target Vowel and Direction in Hungarian. Shorter bars indicate less coarticulation. Error bars display one standard deviation above and below the mean. *** indicates $p < .001$, ** indicates $p < .01$, and * indicates $p < .05$. DM denotes "difference in means."

and Direction, along with results from pairwise comparisons. As can be seen, for target /ɔ/, the magnitude of carryover coarticulation outweighed anticipatory, while anticipatory coarticulation outweighed carryover for target /ɛ/.

With regard to the remaining main effects, the results indicated that the magnitude of coarticulation was substantially impacted by trigger vowel identity, intervening consonant identity, and time point. The significant effect of Trigger ($F(2, 16.530) = 10.396$, $p = .001$) pointed to the role of trigger vowel identity in determining magnitude of coarticulation. Pairwise comparisons showed that /i/ induced significantly greater coarticulation ($M = 0.040$) than /ɛ/ ($M = 0.006$, $p = .001$) or /ɔ/ ($M = 0.013$, $p = .009$). The significant effect of Consonant ($F(2, 15.577) = 64.306$, $p < .001$) highlighted how some consonants permitted greater VV coarticulation across them, while others were more adept at blocking VV coarticulation. Pairwise comparisons showed that /k/ accompanied greater VV coarticulation ($M = 0.070$) than /f/ ($M = 0.002$, $p < .001$) or /p/ ($M = -0.013$, $p < .001$). (No significant difference existed between /f/ and /p/.) Finally, the significant effect of Time Point ($F(1, 7184.949) = 127.164$, $p < .001$) operated in the opposite to expected direction. The predicted outcome for Time Point is that coarticulation will decrease from edge to midpoint; however, in this model, the magnitude of coarticulation increased from edge ($M = 0.009$) to midpoint ($M = 0.030$). This unexpected result may be tied to the use of canonical means averaged across Time Point and Consonant, incorporating unidentified effects of CV coarticulation. Similarly, interactions between CV and VV effects at vowel edge may in some cases reduce the F2 difference score, and imbalances in the number of target words per consonant condition may effectively grant greater weight to some CV effects over others. Some or all of these circumstances may account for the unexpected increase of coarticulation from edge to midpoint.

In summary, the F2 magnitude model found that carryover coarticulation was greater than anticipatory for target /ɔ/, while the opposite was true for target /ɛ/. /i/ triggered greater coarticulation than /ɔ/ or /ɛ/, and /k/ accompanied the strongest VV coarticulation. Contrary to expectations, VV coarticulatory effects were also greater at midpoint than at edge.

4.4. Discussion

In this chapter, I have presented the results of analyses of the presence and magnitude of vowel-to-vowel coarticulation in Hungarian across two target vowels (/ɛ/ and /ɔ/), three trigger vowels (/ɛ/, /ɔ/, and /i/), three consonants (/k/, /f/, and /p/), two directions, and two time points. In the next section, I will relate the results to the two theories proposed in § 1.1 to predict coarticulatory directionality, and I will address unexpected results, such as the ability of /f/ and /p/ to block coarticulation more effectively than /k/, the appearance of dissimilation in one condition, and the apparent increase of coarticulation from edge to midpoint in one model. Figure 36 presents a visual summary of target – trigger effects for the reader's convenience, averaged across directions, consonants, and time points.

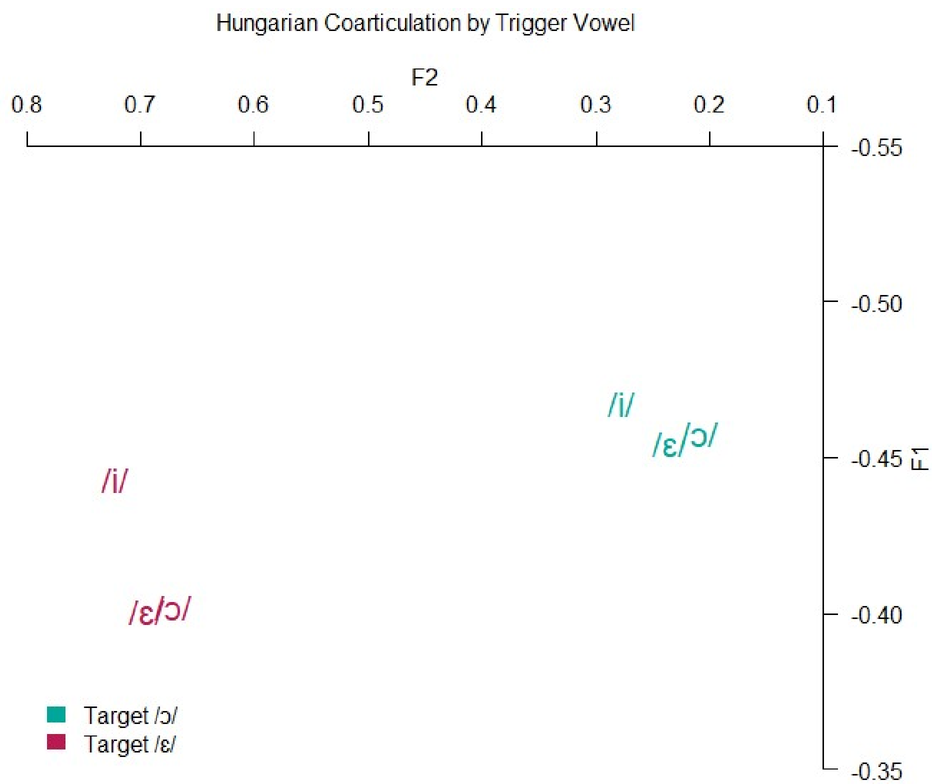

Figure 36: Hungarian coarticulation by trigger vowel. Plotted vowels represent trigger vowel; color represents target vowel. Y-axis is magnified for ease of interpretation.

4.4.1. Directional preference

4.4.1.1. F2

F2 coarticulation was widespread in both directions; its duration was greater, persisting to midpoint, when it was induced by /i/ than by /ɛ/ or /ɔ/. Significant effects arose more frequently in the carryover direction than the anticipatory and with /k/ compared to /f/ and /p/, but some effects for each direction and consonant were attested. With regard to magnitude, target /ɔ/

exhibited greater carryover coarticulation, while target /ɛ/ showed larger anticipatory effects. Thus, the general finding with regard to directionality in F2 coarticulation was that Hungarian exhibited no clear preference for one direction over the other; significant effects appeared more frequently in the anticipatory direction, but the greater magnitude was split across directions by target vowels. This ambivalence does not lend clear support to any of the theories competing for precedence in this dissertation, two of which predict dominant carryover coarticulation in Hungarian and one of which predicts prevalent anticipatory effects.

The first theory predicting a preference for carryover coarticulation in Hungarian focuses on word-level prominence, claiming that the strongest VV coarticulation should move outward from the most prominent – and therefore most stable – vowel. In Hungarian, with its word-initial prominence, this corresponds to carryover coarticulation. Similarly, past work has posited a parallel link between the direction of coarticulation and the direction of vowel harmony in harmonizing languages, such as that found in Wolof and Pulaar by Dye (2015). The third theory, which predicts anticipatory coarticulation in Hungarian, suggests that vowel harmony, while arising from coarticulation, may systematically accompany coarticulation with the opposite directionality once it is phonologized (Beddor & Yavuz, 1995; Conklin, 2015). However, the data presented here consist of a simultaneous surfacing of both directions of coarticulation. This can be accounted for in one of two ways: either as a blend of stress-induced carryover coarticulation and harmony-related anticipatory coarticulation, or as a complete denial of the influence of harmony in determining coarticulatory direction, coupled with a partial affirmation of stress-induced carryover effects. In both accounts, the presence of carryover coarticulation is attributed to the stability of the stressed syllable as a strong trigger and weak target of coarticulation. Anticipatory coarticulation, by contrast, is attributed by the first account to the suppressive effect of vowel harmony, which could also account for the Tatar data, but fails to apply to Dye's (2015) study of Wolof and Pulaar. The second account justifies the presence of anticipatory coarticulation as a language-specific property little influenced by either the position of stress or the direction of harmony. In both of these explanations, Hypothesis 6, which predicted carryover coarticulation linked to the presence of left-to-right vowel harmony, is not supported.

4.4.1.2. F1

Height coarticulation measured in F1 was more restricted in Hungarian than the widespread F2 coarticulation; significant F1 effects were only detected between target /ɛ/ and trigger /i/. For this vowel pair, coarticulation occurred across both directions and all three intervening consonants (/k/, /f/, /p/) at vowel edge, but persisted to midpoint only in the anticipatory direction across /k/. Furthermore, F1 effects showed greater magnitude in the carryover direction than the anticipatory, and were larger with /k/ than /f/ or /p/.

The greater magnitude of F1 coarticulation in the carryover direction provides limited support for Hypothesis 5, which posits that the location of stress is an important predictor of coarticulatory direction. Considering that the height dimension does not participate in harmony in Hungarian, it is possible that any impact from the direction of harmony on the direction of coarticulation would not affect height coarticulation, being restricted instead to backness and rounding, just as harmony is. Under this assumption, the larger carryover effects in the F1 dimension are expected, given the hypothesis that stressed vowels generate the strongest coarticulation. However, strength of coarticulation may be reflected not only in magnitude, but also duration. The single effect that remained statistically significant at midpoint – that is, the one with the greatest duration – was an anticipatory effect, demonstrating that, in height, as in backness, the directional preference of Hungarian is mixed across directions. Additionally, the assumption that height coarticulation remains unaffected by backness harmony demands more evidence before being adopted.

That F1 coarticulation was only significant between /ɛ/ and /i/ merits further consideration. The only other target vowel incorporated into the Hungarian study was /ɔ/, meaning that this finding amounts to a simple dichotomy: /i/ triggered coarticulation in /ɛ/ but not /ɔ/. Both /i/ and /ɛ/ are front vowels; they are also both neutral vowels, transparent to the effects of vowel harmony. This shared frontness (or shared neutrality) may play a role in the susceptibility of /ɛ/ to coarticulation with /i/, perhaps allowing the tongue to move more freely in the height dimension as the largest dimension of difference. If this is so, the larger difference in tongue position along the front-back axis between /ɔ/ and /i/ may limit F1 coarticulation in favor of F2.

4.4.2. Consonantal preference

With regard to consonant, the emergence of greater and more frequent coarticulation across intervening /k/ than /f/ or /p/ is also unexpected. Past research has found that labials tend to permit VV coarticulation to a greater degree than non-labials (Fowler & Brancazio, 2000; Modarresi et al., 2004), though, among the non-labial consonants, velar stops have often been found to be the least likely to block VV coarticulation (Fletcher, 2004; Fowler & Brancazio, 2000). Despite these trends, /f/ was also found to block coarticulation more than a non-labial consonant (/r/) in the corresponding study on Tatar; the repetition of this behavior in Hungarian suggests a cross-linguistic trend with regard to /f/. However, the lacking and lesser coarticulation across /p/ is harder to explain. It is likely that CV coarticulation played a role in this, particularly in the magnitude model, where canonical means were calculated across consonants. CV coarticulatory effects on canonical vowels were far stronger for /k/ than for /f/ or /p/, which may have inflated the F2 difference scores for target words with /k/, particularly those with target /ɔ/, where the fronting effect of /k/ would have aligned with and compounded the fronting effect of VV coarticulation.

4.4.3. Apparent dissimilation

Another unexpected result that deserves attention is the dissimilation found in the F1 edge model in anticipatory coarticulation between target /ɛ/ and trigger /ɔ/ across /k/. At first glance, the appearance of significant dissimilation is both unexpected and perplexing, but a better understanding of the underlying data will relieve some of the confusion. The effect in question was labeled dissimilation because the coarticulated mean of /ɛ/ under the influence of /ɔ/ was higher, not lower, than the canonical mean of /ɛ/ in the same conditions. Since the grand canonical mean of /ɔ/ across conditions was lower than that of /ɛ/ and the significant difference for the relevant coarticulated condition is in the opposite to expected direction, the effect was labeled dissimilation. In this section, I will show that, despite the assigned label, the significant difference should more properly be considered coarticulation.

The relative height of /ɛ/ and /ɔ/, parametrized in normalized F1, is not consistent across participants. Five of the twenty participants have a higher canonical F1 mean for /ɔ/ than /ɛ/, and this proportion increases when canonical means are calculated for the anticipatory edge condition near /k/: nine out of twenty participants have a higher canonical mean for /ɔ/ than /ɛ/ in the anticipatory edge condition before /k/. Thus, claiming that a change between /ɔ/ and /ɛ/ in one direction or the other in the F1 dimension represents coarticulation is tenuous at best. Let us consider the differences in means behind the troubling effect for each participant. Fifteen participants had a higher F1 in the coarticulated condition than the canonical, driving the effect. Of those fifteen participants, nine had a higher F1 for canonical /ɔ/ than /ɛ/ in this condition: therefore, the corresponding increase should be considered, for these nine participants, to be coarticulation not dissimilation. The other six had a higher canonical F1 for /ɛ/, and the raise in coarticulated /ɛ/ must therefore be labeled dissimilation for these participants. Finally, the remaining five participants showed coarticulation relative to their own canonical mean, with /ɛ/ lowering in /ɔ/ context; these participants' results did not drive this effect. This is summarized in Table 18**Error! Reference source not found.**.

Table 18: Count of participants by relative F1 of canonical and coarticulated /ɔ/ and /ɛ/ in anticipatory edge context near /k/ in Hungarian.

<table>
<tr><th>Canonical means in relevant conditions</th><th>N</th><th>Difference in means between coarticulated and canonical words</th><th>Best labeled as:</th><th>N</th><th>Drove effect?</th></tr>
<tr><td rowspan="2">F1 of canonical /ɔ/ higher than F1 of canonical /ɛ/</td><td rowspan="2">9</td><td>F1 of /ɛ/ raised in /ɔ/ context</td><td>Coarticulation</td><td>9</td><td>Yes</td></tr>
<tr><td>F1 of /ɛ/ lowered in /ɔ/ context</td><td>Dissimilation</td><td>0</td><td>No</td></tr>
<tr><td rowspan="2">F1 of canonical /ɔ/ lower than F1 of canonical /ɛ/</td><td rowspan="2">11</td><td>F1 of /ɛ/ raised in /ɔ/ context</td><td>Dissimilation</td><td>6</td><td>Yes</td></tr>
<tr><td>F1 of /ɛ/ lowered in /ɔ/ context</td><td>Coarticulation</td><td>5</td><td>No</td></tr>
</table>

The key takeaway from this exploration of the data is that, although this effect appears dissimilatory when judging by grand means across conditions and participants, it is actually driven by shifts in the coarticulatory direction for fourteen out of twenty participants. However, the relative F1 of canonical /ɔ/ and /ɛ/ is not consistent across participants, reflecting their shared status as mid-low vowels. Thus, the full context makes it clear that the troubling "dissimilation" label of the effect in question was too hastily assigned and that the effect is better understood as coarticulatory. Furthermore, this discussion makes it clear that it is wise to be cautious in assigning labels of coarticulation or dissimilation to any significant F1 shifts across /ɔ/ and /ɛ/, given how closely their canonical F1 values align.

4.4.4. Time Point

The final unexpected effect found in this chapter was the increase of coarticulation from edge to midpoint in the F2 magnitude model. In practically all studies of VV coarticulation, effects are strongest closer to the triggering vowel and weaken with increased distance from the trigger. The reversal found in the current data may be attributable to CV coarticulation in one of two ways: either because the use of a canonical mean averaged across consonants inflated difference scores for some target words, or because CV coarticulation counteracted VV effects at vowel edge, lowering edge difference scores but not midpoint scores. Future analyses can explore these possibilities by testing alternative methods of computing difference scores. One tactic that may increase accuracy is to compute the canonical means for each condition of Participant, Vowel, Consonant, and Time Point, thus ensuring that difference scores take each minimal pair into account. For some conditions in the dataset, these means and difference scores could be made even more specific by accounting for the initial consonant, thus minimizing the impact of CV coarticulation from that segment as well as the intervening consonant.

4.4.5. Conclusion

In this chapter, I have examined VV coarticulation in Hungarian and found F2 coarticulation in both directions. F1 coarticulation was more limited, with significant effects induced only in /ɛ/, and then only by /i/, out of the vowels examined. This finding is attributed to the shared frontness of /ɛ/ and /i/. Furthermore, while anticipatory coarticulation is present across a wider range of vowel and consonant conditions, carryover effects have a greater magnitude than anticipatory for one of the two target vowels (namely, /ɔ/). The presence of both carryover and anticipatory coarticulation in F2 supports an analysis in which neither stress nor the direction of harmony is the sole predictor of coarticulatory direction in harmonizing languages.

5. CONCLUSION

In this dissertation, I have presented original acoustic data from Spanish, Tatar, and Hungarian to address the nature of the synchronic relationship between word-level stress, coarticulatory direction, and the direction of vowel harmony in the first study of front-back vowel harmony to examine the interplay of these three phenomena. Data from Spanish provided a snapshot of coarticulation under a variety of stress conditions without vowel harmony, while Tatar and Hungarian offered insight into harmonizing languages with opposite stress profiles. In this conclusion, I will review key trends emerging from these three studies and attempt to highlight the underlying cross-linguistic reality behind their diverse findings. As I will demonstrate, no single principle can capture the relationship between stress, direction of harmony, and the dominant direction of VV coarticulation across languages. Instead, I will situate the findings of the three studies within the life-cycle understanding of phonologization proposed by Hyman (2013; 1976).

5.1. Key findings

5.1.1. Spanish

The primary purpose of the Spanish study was to test the effect of stress on VV coarticulation and determine whether previous results finding that stressed vowels are more stable and coarticulate less (see, e.g., Fowler, 1981; Magen, 1997; Majors, 2006; Recasens, 2015) apply to Spanish and, if so, whether this effect is due to reduced coarticulation in stressed targets or enhanced coarticulation with stressed triggers. The Spanish study found that coarticulation was both less frequent and of lesser magnitude when stress fell on the target vowel, while the effect of stress falling on the trigger vowel was mixed. For unstressed targets, stressed triggers enhanced coarticulation in the carryover direction, but not the anticipatory. Thus, the Spanish study supported previous findings (Farnetani, 1990; Fowler, 1981; Magen, 1997; Majors, 2006; Mok, 2012; Nicolaidis, 1999; Recasens, 2015) that unstressed vowels coarticulate more than stressed vowels.

The Spanish study focused on mid vowels /e/ and /o/ as targets of coarticulation, with /p/ and /k/ as intervening consonants. Two key asymmetries in susceptibility to coarticulation across target vowels and intervening consonants emerged. Though the magnitude of coarticulation was similar across target vowels /e/ and /o/, /e/ exhibited measurable VV coarticulation under more stress conditions than /o/. Additionally, coarticulatory affiliations between /e/ and /p/ and between /o/ and /k/ emerged: the magnitude of coarticulation measured in /e/ was greater in target words with intervening /p/, while for target /o/, intervening /k/ was associated with greater coarticulation. These affiliations were attributed to acoustic reinforcement of the VV effects by complementary CV effects. When the VV and CV effects aligned to induce the same type of acoustic changes, the additive effect that emerged appeared greater than its counterparts.

A final key finding in the Spanish data related to direction of coarticulation. Carryover VV effects displayed a greater magnitude and duration than anticipatory ones in the Spanish data. This asymmetry may be an inherent trait of the Spanish language, or it may be an artifact of English bilingualism. Additional research is required to address this question.

5.1.2. Tatar

In the Tatar chapter, I presented the first acoustic analysis of the Tatar vocalic system, establishing formant ranges for the ten vowel phonemes and investigating key qualities of the vowel space. Two of these qualities were crowding around the center of the vowel space and high F2 variability (found particularly in stressed high round vowels). Both are explained through the presence of vowel harmony, which minimizes the need for a strong front-back contrast outside the initial syllable. The Tatar vowel system also provides a fascinating example of phonology influencing phonetics, with implications for formal models of the phonetics-phonology interface.

The analysis of Tatar coarticulation suffered changes to its intended design due to frequent unexpected harmonization in [ɒCæ] and [æCɑ] items, which rendered it impossible to examine coarticulatory changes in these items. However, the unexpected harmonization itself provides a promising avenue for future research, with some initial indications that orthographically disharmonic loan words may tend to harmonize to the stressed syllable at the time of borrowing.

Alteration to the initial design allowed the analysis of Tatar coarticulation to proceed with a focus on the relationship between trigger /i/ and targets /ɑ, æ/. In this analysis, anticipatory coarticulation predominated over carryover, and /r/ permitted more VV coarticulation across it than /f/. Vowel identity also helped predict what types of effects would be strongest: /æ/ tended to exhibit F1 effects, while /ɑ/ generally coarticulated more in F2. This asymmetry was attributed to the shared frontness of /i/ and /æ/ and the stark difference in backness between /i/ and /ɑ/, which discouraged large F2 effects in /æ/ and encouraged them in /ɑ/.

5.1.3. Hungarian

The study on Hungarian VV coarticulation found limited height coarticulation, while F2 coarticulation occurred across more conditions. No strong preference for either direction of coarticulation emerged. Instead, anticipatory coarticulation enjoyed greater precedence in that it was statistically measurable across a wider range of conditions, but dominance in magnitude was split across directions by target vowel. Carryover effects were of greater magnitude for target /ɔ/, and anticipatory effects were greater for target /ɛ/. Thus, a number of striking divisions in the results prevented the assignment of a single prevalent direction for VV coarticulation in Hungarian.

The Hungarian data also contained two results whose full explanation lies beyond the scope of this dissertation, demanding further investigation. The first is the consonantal asymmetry in Hungarian VV coarticulation, where coarticulation was detected in /k/ context more often than with intervening /f/ or /p/. Labials – or at least, labial stops – are generally predicted and observed to freely permit VV coarticulation across them, so the lack of statistically detectable coarticulation across /p/ is surprising. This unexpected result may be due to the combined effect of consonant-vowel affiliations suppressing or encouraging VV coarticulation, such as those observed in Tatar, and asymmetries in the set of target words. Alternatively, the roots of this phenomenon may lie in an as-yet-unexplored direction.

The second unexpected result in the Hungarian data related to the factor Time Point, referring to the two measurement points for coarticulation used in this dissertation, vowel midpoint and vowel edge. The expected behavior is that measurements taken at vowel edge (always the one nearest the trigger vowel) will generally demonstrate greater coarticulation than those taken at midpoint, as coarticulation decreases with distance from the trigger. However, this expected behavior was notably lacking in the model analyzing the magnitude of Hungarian F2 coarticulation, a lack attributed to the method of computing difference scores for that model.

Future work focusing on the differing outcomes associated with more and less fine-tuned difference scores will aid in the interpretation of this particular model from the Hungarian chapter.

5.2. Stress, coarticulation, and vowel harmony

The primary goal of this dissertation was to examine the relationships among stress, VV coarticulation, and vowel harmony, using three languages – Spanish, Tatar, and Hungarian – as test cases. The Spanish study examined the effect of stress on VV coarticulation with no interference from vowel harmony, which is absent in Spanish,[3] and found that stressed vowels generally coarticulate less than unstressed ones, confirming the results of previous work on other languages (see, e.g., Fowler, 1981; Magen, 1997; Majors, 2006; Recasens, 2015). Because of this, if the influence of stress on coarticulation was consistent across languages, I expected Tatar's word-final stress to correspond to stronger anticipatory coarticulation and Hungarian's word-initial prominence to give preference to carryover coarticulation.

The purpose of including Tatar and Hungarian in this dissertation was to better understand how the directions of harmony and coarticulation relate synchronically while accounting for the mitigating effect of stress. In Tatar, the magnitude of coarticulation was greater in the anticipatory direction, though carryover effects were also attested. This was true with regard to both height and backness: in the backness dimension, some orthographically disharmonic lexemes also underwent unexpected harmonization, which may be considered complete coarticulation, most often in the anticipatory direction. This corresponded with the predictions related to stress as well as the theory that harmony will actively suppress parallel coarticulation, but failed to support the idea that harmony will promote coarticulation in the same direction. In Hungarian, where carryover coarticulation was predicted to dominate due to its word-initial stress and in order to maintain a parallel to the left-to-right direction of harmony, directional outcomes were mixed. Anticipatory coarticulation was statistically significant across a wider range of conditions than carryover with regard to both height and backness, but carryover effects had a greater magnitude than anticipatory in most conditions. These mixed

[3] With the exception of some European dialects not present in the current study; see, e.g., Henriksen (2017).

results may reflect a compromise between coarticulatory direction generated by stress (carryover) and the opposite direction, which opposes the direction of vowel harmony (anticipatory). Alternatively, the mixed results may simply correspond to other language-specific particulars, such as nuances of vowel and consonant articulation and prosodic patterns. The unexpected mix of anticipatory and carryover coarticulation in Hungarian highlights the inherent complexity and variability of coarticulation data; while strong directional preferences for VV coarticulation appear in some languages, they are not present in all tongues. Neither vowel harmony nor stress can fully predict the dominant direction of VV coarticulation, although coarticulation is always reduced for stressed targets.

Given these results, the idea that the direction of coarticulation will cleanly parallel or routinely oppose the direction of harmony in any given harmonizing language must be rejected. Simple parallels do not account for the multitudinous host of influences shaping coarticulatory magnitude, direction, and duration. Neither the Tatar data nor the Hungarian results support the notion that an inherent synchronic parallel between the directions of harmony and coarticulation exists in all harmonizing languages. Similarly, data from Dye's (2015) work on Wolof and Pulaar makes it clear that the prevailing directions of harmony and coarticulation need not be opposed to one another. This lack of a consistent parallel between the directions of harmony and coarticulation demonstrates that this pair of processes do not function like other phonetic doublets, which habitually exhibit suppression of the phonetic process by the corresponding phonological one. Instead, the temporal remove between harmony and coarticulation that prevents both processes from operating simultaneously in a single dimension appears sufficient to mitigate the suppressing effect found in other doublets. Thus, the results indicate that, while stress is partially predictive of the dominant direction of coarticulation, the direction of vowel harmony is a poor predictor indeed. In the next section, I will propose a method of relating direction of vowel harmony and direction of coarticulation in synchronic analyses using diachronic information.

5.3. The role of phonologization in understanding stress and vowel harmony

When it comes to coarticulation and harmony, diachrony and synchrony cannot be easily divorced. Considering the relationship of harmony and coarticulation within the life cycle of phonologization is the key to unraveling these apparent typological contradictions. Hyman

(2013; 1976) summarizes a "life cycle" view of phonological processes, wherein the phonologization of a phonetic process is followed by morphologization, lexicalization, and ultimately loss. Every process that is elevated from phonetics to phonology will eventually migrate to the morphology, dwindle to a lexically encoded shadow of its former self, and gradually fade beyond recall: this natural progression reflects the expected fate of all phonological processes, given sufficient time. As I will demonstrate, phonologization presents a promising framework within which the synchronic relationship of direction of harmony, direction of coarticulation, and stress can be contextualized.

Given ample evidence that coarticulation tends to move outward from the stressed syllable, the premise that direction of harmony and direction of coarticulation generally align upon first phonologization appears well-supported. In some harmony systems, such as the stress-dependent harmonies described in Majors (2006), the stress-dependent nature of the assimilatory process is phonologized as part of the harmony system itself. However, the purpose of this discussion is to propose an explanation of the diversity of attested harmonic systems – those with a stress-dependent mechanism and those without, those where direction of coarticulation parallels the direction of harmony and those where it does not. Within this framework, the synchronic relationship between diachronically related processes relates at least in part to the stage of the diachronic life cycle the process in question currently occupies. Languages with less similarity between harmony and coarticulation – such as Turkish and Tatar – may have progressed further through the life cycle of harmony than those like Wolof, where close parallels still exist across harmony and coarticulation.

In progressing toward loss, it is not the passage of real time that is relevant, but the accumulation of phonological changes, what I will refer to as phonological time. Elapsed time is irrelevant; only phonological time matters. It is entirely possible for two languages to progress through the phonologization cycle in the same way, but at different rates. Naturally, some correlation is expected between phonological time and elapsed or real time. No language is stagnant, and the greater the period of real time that has passed, the more opportunities a language will have had to accumulate phonological changes, corresponding to greater phonological time. Therefore, in languages where substantial alteration to factors impacting coarticulatory behavior has occurred after harmony was phonologized, the possibility of divergence between the directions of harmony and coarticulation is greater than in languages for which harmony is a relatively recent phenomenon.

Let us consider the contrast between Turkish and Tatar, which feature left-to-right vowel harmony, right-to-left coarticulation, and word-final stress, and Wolof, which features initial stress, left-to-right harmony, and left-to-right coarticulation. As discussed in § 3.1.2, Turkic stress has not always rested on the final syllable; earlier forms of Turkic featured a form of stress on the initial syllable (Chen, 2005; Menges, 1995). This stress is believed to have shifted to the final syllable after the emergence of vowel harmony. Thus, in the first stage of phonologization, word-initial stress and correspondingly prevalent left-to-right coarticulation gave rise to left-to-right vowel harmony, which, upon entering the phonology, gained an independent existence of its own. At some point after this, stress shifted to the final syllable, and coarticulatory direction shifted with it. This change to the position of stress points to the passing of phonological time as the language undergoes change from the state it was in when harmony first emerged. In Tatar, it seems likely that the shift in the position of stress has not only affected coarticulation, but may even be affecting harmony, driving phonological change towards loss or reanalysis of the harmony process. (See § 3.3.3.2.4 for a discussion of the unexpected forms of harmony that appeared in the present study.) This passage of relevant phonological time embodied in the stress shift ought to be pushing the Tatar harmony process further through the phonologization life cycle, and evidence from other aspects of the language suggest that harmony is indeed in the morphologization stage. Specifically, the lack of harmony in the roots of new loan words, particularly Russian loans, suggests that harmony no longer occupies pride of place in Tatar phonology.

It does not follow that coarticulation will fail to parallel harmony in all languages whose harmony processes are approaching morphologization, lexicalization, or loss, nor that all languages with recently emergent harmony will exhibit predominantly parallel coarticulation (particularly if a relevant change, such as a stress shift, has occurred – hence the importance of the distinction between elapsed and phonological time). A language such as Wolof, in which coarticulation moves outward from the stressed syllable and the directions of harmony and coarticulation still align (see Dye, 2015), may be supposed to have undergone relatively fewer relevant phonological changes (phonological time) than Tatar. However, there is no reason to suppose that harmony in Wolof, where coarticulation and harmony run in parallel, is necessarily younger than Tatar harmony, which runs opposite the strongest VV coarticulation in that language. Rather, it may be mere chance that Wolof has not undergone any phonological changes suited to initiate a change in the direction of coarticulation. In the same vein, it is easy to imagine a language in which the directions of harmony and coarticulation were delinked relatively soon upon the phonologization of harmony simply due to the chance arrival of an ideally equipped phonological change, or a language in which no such change ever appears and harmony and coarticulation proceed merrily in parallel through all the stages of the life cycle until harmony is finally lost.

Naturally, the life cycle view is not the only possible explanation for the unexpected patterns observed across harmonizing languages. In order to verify the use of this framework, several types of evidence should be pursued. Information about the emergence and age of the harmony processes in these languages is high on the list of unknowns needed to substantiate this theory. A close second is any linguistic evidence that places harmony in either the phonology, the morphology, or the lexicon in a given language. Finally, counterevidence that disputes or disproves the application of the phonologization framework in this way is also desirable. After all, other explanations for the delinking of stress and coarticulatory direction from harmonic direction are possible, and it must be acknowledged that the present discussion is highly speculative.

Languages like Hungarian and Pulaar may prove to be the source of such counterevidence, as neither fits cleanly into the proposed framework. In the case of Hungarian, where both directions of coarticulation are prominent in different ways, the framework does not provide a means of differentiating between directional dominance in frequency of occurrence, duration, and magnitude. Future work focused on clarifying the connection between stress and coarticulation may be useful in refining linguistic understanding of the Hungarian data presented in this dissertation and make clear how it best fits within the proposed framework. Linking stress – or particular acoustic realizations of stress, such as increases in intensity or changes in pitch – to specific types of changes in coarticulation, such as increases in magnitude, lengthened duration, or higher frequency of occurrence across vowel and consonant conditions will also have implications for the study of coarticulation beyond the evaluation of this particular framework.

The Pulaar language, described in Dye's (2015) dissertation, features word-initial stress, right-to-left harmony, and right-to-left coarticulation. At first glance, this language does not fit within the proposed framework at all, given present assumptions. For right-to-left harmony to emerge, one would expect that stress was once word-final and be forced to propose the existence of a past stress shift to word-initial position. However, right-to-left coarticulation would be expected to be overpowered by left-to-right coarticulation at the time of the stress shift, and according to the data presented in Dye (2015), this is not the case. Future work on the ideas proposed in this section should pay careful attention to Dye's (2015) Pulaar data to determine if it constitutes strong enough counterevidence to refute the proposed framework or if it can be explained by exceptions related to the type of harmony or coarticulation examined, other phonetic or phonological facts about Pulaar, or differences in methodology across studies.

In this section, I have proposed a framework for understanding the relationship between direction of vowel harmony, direction of VV coarticulation, and position of stress based on Hyman's (2013; 1976) life-cycle model of phonologization. Within this framework, the amount of phonological time, understood as relevant phonological changes, that has elapsed since the phonologization of a particular phenomenon (in this case, vowel harmony) determines the probability that a phonological process will exhibit different behavior from the phonetic process it evolved from (here, VV coarticulation). Greater phonological time increases the probability that the two processes will exhibit different behaviors, such as harmony and coarticulation proceeding in opposite directions. However, neither the passage of phonological nor real time guarantees that related phonetic and phonological processes will diverge; it merely increases the probability. The passage of phonological time also pushes phonological processes into later stages in their life cycle (morphologization and lexicalization). Thus, the framework predicts a correlation between phonological processes that are demonstrably in the lexical or morphological stages of degradation and those that have diverged from their phonetic parent process in notable ways.

5.4. Intervening consonant and coarticulation

In multiple studies of the impact of intervening consonants on VV coarticulation, labials are found to allow the greatest amount of coarticulation (see, e.g., Fowler & Brancazio, 2000; Modarresi, Sussmann, Lindblom, & Burlingame, 2004) compared to lingual consonants, but in two out of three languages explored here, this trend did not hold true. In Spanish, greater VV coarticulation was found across /p/ than /k/, but Tatar coarticulation was greater across /r/ than the labial /f/, and in Hungarian, the greatest coarticulation traversed intervening /k/, outweighing both /f/ and /p/. Thus, in addition to refuting previous generalizations about the interaction between the directions of harmony and coarticulation, my data reinforce how strongly consonantal impacts on VV coarticulation can vary across languages (as explored more deeply in Recasens, Farnetani, Fontdevila, & Pallarès, 1993).

5.5. Summary

In this dissertation, I have demonstrated that stressed vowels undergo less coarticulation in both harmonizing and non-harmonizing languages, with the strongest impact of stress on degree of coarticulation clearly tied to the presence or absence of stress on the target vowel, not the trigger. I further concluded that the direction of VV coarticulation is under no synchronic obligation to parallel or oppose the direction of vowel harmony and posited that the degree of progress the harmony process has made through its phonologization life cycle may have a strong impact on the direction of coarticulation. In particular, changes to the phonology that have arisen since the phonologization of harmony, such as the shift of stress from one position to another, are expected to correspond to changes in the direction of coarticulation. Finally, I observed that the degree of coarticulation permitted across /p/, /k/, and /f/ is not consistent across languages.

5.6. Future directions & limitations

A number of factors varied across the three languages analyzed in this dissertation, presenting obvious limitations to the interpretation of results. Variation in vowels tested, intervening consonant, and the existence or non-existence of target items for each language constitute the most obvious. Additionally, variation in the vowel inventories and, for Tatar and Hungarian, the harmony systems may have played a role in shaping results. For Hungarian in particular, the use of neutral vowels as a stand-in for harmonically front vowels presents a potential confound that future studies may remedy by including a wider subset of Hungarian vowel phonemes.

With regard to Tatar, a number of avenues for future research emerge from this dissertation. The Tatar study presented evidence that Tatar harmony may be undergoing reanalysis, at least with regard to disharmonic items: three out of four orthographically disharmonic test items underwent unexpected harmonization in the direction opposite that of established harmony. These items, which constitute a marginalized subset of Tatar phonology, frequently harmonized to the most stable vowel of the root, the stressed vowel. Future research should test a wider array of orthographically disharmonic items, investigate the sociophonetic implications of competing pronunciations, discover how affix selection is governed for such items, and generally quantify the nature and extent of any ongoing changes to the Tatar harmony system. Additionally, further investigation into the times when various Tatar loans were adopted into the language can shed light on stress patterns for early loans and clarify what form of stress-dependent harmonization would be expected for particular loans. Such information would allow for a more accurate and in-depth analysis of optional harmony patterns in orthographically disharmonic words.

An additional avenue for future research resides in the Turkish language, where some minimal pairs of proper and common nouns are differentiated by stress. Building on the groundwork laid down by Beddor & Yavuz (1995), a future study could investigate the role of stress in shaping coarticulation in Turkish by analyzing such pairs. These exceptions to the general rule of Turkish word-final prominence have the potential to provide an illuminating view of the acoustic consequences of stress in that language and could furnish a clearer picture of the interactions between stress, harmony, and coarticulation in a single language.

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APPENDIX A. TARGET WORDS

Spanish

All Spanish target words are non-words.

Spanish	IPA	Non-word
kekéke	/keˈkeke/	*non-word*
kekeké	/kekeˈke/	*non-word*
kékeke	/ˈkekeke/	*non-word*
kekéko	/keˈkeko/	*non-word*
kekekó	/kekeˈko/	*non-word*
kékeko	/ˈkekeko/	*non-word*
kekóko	/keˈkoko/	*non-word*
kekokó	/kekoˈko/	*non-word*
kékoko	/ˈkekoko/	*non-word*
kokéke	/koˈkeke/	*non-word*
kokeké	/kokeˈke/	*non-word*
kókeke	/ˈkokeke/	*non-word*
kokóke	/koˈkoke/	*non-word*
kokoké	/kokoˈke/	*non-word*
kókoke	/ˈkokoke/	*non-word*
kokóko	/koˈkoko/	*non-word*
kokokó	/kokoˈko/	*non-word*
kókoko	/ˈkokoko/	*non-word*
pepépe	/peˈpepe/	*non-word*
pepepé	/pepeˈpe/	*non-word*
pépepe	/ˈpepepe/	*non-word*
pepépo	/peˈpepo/	*non-word*
pepepó	/pepeˈpo/	*non-word*
pépepo	/ˈpepepo/	*non-word*
pepópo	/peˈpopo/	*non-word*
pepopó	/pepoˈpo/	*non-word*
pépopo	/ˈpepopo/	*non-word*
popépe	/poˈpepe/	*non-word*
popepé	/popeˈpe/	*non-word*
pópepe	/ˈpopepe/	*non-word*
popópe	/poˈpope/	*non-word*
popopé	/popoˈpe/	*non-word*
pópope	/ˈpopope/	*non-word*
popópo	/poˈpopo/	*non-word*
popopó	/popoˈpo/	*non-word*
pópopo	/ˈpopopo/	*non-word*

Tatar

All Tatar target words are real words.

Tatar	IPA	Gloss
афәт	/ɒfæt/	trouble, death
Сафа	/sɒfɑ/	a proper name
зифа	/zifɑ/	shapely, harmonious
җәфа	/ʑæfɑ/	torment, suffering
гафил	/gɒfil/	careless, negligent
нәфис	/næfis/	elegant, refined; artistic
мәгърифәт	/mæʁrifæt/	education
сәхифә	/sæxifæ/	page in history
сәфәр	/sæfær/	second month of calendar by moon; trip, voyage
гарәп	/gɒræp/	Arabic
ара	/ɒrɑ/	interval
шәрә	/ʃæræ/	nude
шәраб	/ʃærɑb/	wine
тарих	/tɒrix/	history
жираф	/ʑirɑf/	giraffe
зирәк	/ziræk/	shrewd, bright, smart
пәри	/pæri/	fairy
фәлсәфә	/fælsæfæ/	philosophy
әфәнде	/æfænde/	gentleman
урам	/urɑm/	street
укыту	/uqətu/	teaching
урман	/urmɑn/	forest
корылык	/qorələq/	drought
борыч	/borəɕ/	pepper, vegetable
колак	/qolɑq/	ear
өрек	/ørek/	dried apricot
мөгез	/møgez/	horn
абый	/ɒbɨj/	brother, uncle
сыйфат	/sɨjfɑt/	quality
кыйбат	/qɨjbɑt/	expensive
үрмәкүч	/ʉrmækʉɕ/	spider
күрше	/kʉrʃe/	neighbor
бүлек	/bʉlek/	chapter
ипи	/ipi/	bread
сишәмбе	/siʃæmbe/	Tuesday
кисәк	/kisæk/	piece, bit
сәке	/sæke/	plank bed
акыл	/ɒqɨl/	mind

Hungarian

Hungarian	IPA	Gloss
afa	/ɔfɔ/	*non-word*
afe	/ɔfɛ/	*non-word*
afi	/ɔfi/	*non-word*
aka	/ɔkɔ/	*non-word*
ake	/ɔkɛ/	*non-word*
aki	/ɔki/	who
apa	/ɔpɔ/	father
ape	/ɔpɛ/	*non-word*
api	/ɔpi/	*non-word*
efa	/ɛfɔ/	*non-word*
efe	/ɛfɛ/	*non-word*
efi	/ɛfi/	*non-word*
eka	/ɛkɔ/	*non-word*
eke	/ɛkɛ/	plough
eki	/ɛki/	*non-word*
epa	/ɛpɔ/	*non-word*
epe	/ɛpɛ/	gall
epi	/ɛpi/	*non-word*
ifa	/ifɔ/	a type of vehicle
ife	/ifɛ/	*non-word*
ika	/ikɔ/	*non-word*
ike	/ikɛ/	*non-word*
ipa	/ipɔ/	a type of beer
ipe	/ipɛ/	*non-word*
kapa	/kɔpɔ/	hoe
kape	/kɔpɛ/	*non-word*
kapi	/kɔpi/	*non-word*
kepa	/kɛpɔ/	*non-word*
kepe	/kɛpɛ/	*non-word*
kepi	/kɛpi/	*non-word*
kipa	/kipɔ/	a religious cap
kipe	/kipɛ/	*non-word*
taka	/tɔkɔ/	*non-word*
take	/tɔkɛ/	*non-word*
taki	/tɔki/	*non-word*
teka	/tɛkɔ/	*non-word*
teke	/tɛkɛ/	bowl
teki	/tɛki/	nickname for turtle
tika	/tikɔ/	*non-word*
tike	/tikɛ/	*non-word*

APPENDIX B. CARRIER PHRASES

Spanish

Quien ganó el ______ por la mañana fue Carlos.
It was Carlos who won the _________ this morning.

Quien rompió el __________ con un palo fue Thiago.
It was Thiago who broke the __________ with a stick.

Quien llevó el __________ de la escuela fue Paula.[4]
It was Paula who brought the ____________ from school.

Quien limpió el _______ para su hijo fue Emma.
It was Emma who cleaned the ___________ for her son.

Quien usó el __________ como espejo fue Lucas.
It was Lucas who used the ___________ as a mirror.

Quien vendió el ____________ de su hermano fue Marcos.
It was Tomas who sold his brother's ______________.

Quien comió el ____________ fuera del carro fue Mía.
It was Mia who ate the ___________ outside the car.

Quien compró el ___________ para su tía fue Sara.
It was Sara who bought the ____________ for her aunt.

Quien bebió el _________ sobre el techo fue Pablo.
It was Pablo who sipped the _____________ on the roof.

Quien tocó el _________ muy altamente fue Diego.
It was Diego who played the __________________very loudly.

[4] Participants 1 and 2 read this sentence with the name "Lucia". It was subsequently changed to maintain syllable structure and stress placement matching the other phrases.

Tatar

Марат _________ сүзен укый белә.
Marat can read the word _________ .

Ленар _________ сүзен белми.
Lenar doesn’t know the word _________ .

Кәрим _________ сүзен көненә бик күп тапкыр яза.
Kärim writes the word _________ many times during the day.

Дина _________ сүзен өйрәнде.
Dina learned the word _________ .

Алина _________ сүзен яза белә.
Alina can write the word _________ .

Алсу _________ сүзен әйтә.
Alsu says the word _________ .

Гүзәл _________ сүзен ишетми калды.
Marat couldn’t hear the word _________ .

Ринат _________ сүзен һаман куллана.
Güzäl always uses the word _________.

Радик _________ сүзен беренче тапкыр күрә
Radik sees the word _________ for the first time.

Найля _________ сүзенең мәгьнәсен белми.
Naylya doesn’t know the meaning of the word _________ .

Hungarian

Itt az_____________ szó áll.
The_____________ stands here.

Ez az _____________ szó lesz.
This will be the word_____________.

Most az _____________ szó jön.
Now the word _____________ is coming.

APPENDIX C. MODEL RESULTS

Chapter 2: Spanish

Magnitude Model

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	19.359	57.558	p < .001
Stress	2	2232.071	13.724	p < .001
Vowel	1	2221.002	0.011	p = .917
Direction	1	2219.309	137.811	p < .001
Time Point	1	2217.353	81.804	p < .001
Consonant	1	2218.354	319.216	p < .001
Stress by Consonant	2	2218.581	8.299	p < .001
Vowel by Consonant	1	2219.503	1579.112	p < .001
Direction by Consonant	1	2218.46	28.337	p < .001
Time Point by Consonant	1	2217.361	24.409	p < .001
Vowel by Direction	1	2219.537	5.199	p = .023
Stress by Vowel	2	2220.19	21.577	p < .001
Stress by Direction	2	2225.311	63.611	p < .001
Vowel by Time Point	1	2217.361	62.93	p < .001
Time Point by Direction	1	2217.362	4.141	p = .042
Stress by Vowel by Direction	2	2219.339	16.495	p < .001
Stress by Vowel by Consonant	2	2219.264	17.91	p < .001
Vowel by Direction by Consonant	1	2218.362	5.724	p = .017
Vowel by Time Point by Consonant	1	2217.353	84.01	p < .001

Chapter 3: Tatar

F1 Magnitude Model

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	27.025	37.926	p < .001
Target	1	3442.432	24.112	p < .001
Trigger	2	3441.13	15.59	p < .001
Direction	1	3440.134	24.824	p < .001
Time Point	1	3439.256	610.676	p < .001
Consonant	1	3442.903	114.708	p < .001
Target by Consonant	1	3440.888	63.543	p < .001
Trigger by Consonant	2	3441.072	20.545	p < .001
Direction by Consonant	1	3440.362	74.915	p < .001
Time Point by Consonant	1	3439.209	15.071	p < .001
Trigger by Direction	2	3440.72	22.418	p < .001
Target by Trigger	2	3441.222	20.444	p < .001
Target by Direction	1	3440.852	19.185	p < .001
Target by Time Point	1	3439.326	25.761	p < .001
Trigger by Time Point	2	3439.268	179.189	p < .001
Time Point by Direction	1	3439.306	20.235	p < .001
Trigger by Direction by Consonant	2	3440.852	24.781	p < .001
Trigger by Time Point by Consonant	2	3439.164	43.146	p < .001
Time Point by Direction by Consonant	1	3439.164	26.886	p < .001
Trigger by Time Point by Direction	2	3439.266	7.348	p = .001
Target by Trigger by Time Point	2	3439.334	69.507	p < .001
Target by Trigger by Direction	2	3439.948	37.155	p < .001
Target by Trigger by Time Point by Direction	2	3439.233	8.323	p < .001
Target by Trigger by Direction by Consonant	3	3440.647	5.734	p = .001
Target by Time Point by Direction by Consonant	2	3439.225	5.891	p = .003

Chapter 3: Tatar, continued

F2 Magnitude Model

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	26.616	418.659	p < .001
Target	1	3435.68	429.643	p < .001
Trig	2	3435.144	265.62	p < .001
Direction	1	3434.587	22.534	p < .001
Time Point	1	3434.063	6.294	p = .012
Consonant	1	3436.099	187.503	p < .001
Target by Consonant	1	3434.992	309.197	p < .001
Trig by Consonant	2	3435.129	114.617	p < .001
Direction by Consonant	1	3434.496	210.495	p < .001
Time Point by Consonant	1	3434.066	85.278	p < .001
Trig by Direction	2	3435.039	17.367	p < .001
Target by Trig	2	3435.16	773.172	p < .001
Target by Direction	1	3435.027	91.24	p < .001
Trig by Time Point	2	3434.056	3.235	p = .039
Time Point by Direction	1	3434.065	133.816	p < .001
Target by Direction by Consonant	1	3435.253	23.452	p < .001
Target by Time Point by Consonant	1	3434.057	51.289	p < .001
Trig by Direction by Consonant	2	3434.765	34.292	p < .001
Time Point by Direction by Consonant	1	3434.054	16.851	p < .001
Trig by Time Point by Direction	2	3434.068	5.864	p = .003
Target by Trig by Time Point	2	3434.092	37.574	p < .001
Target by Time Point by Direction	1	3434.048	27.422	p < .001
Target by Trig by Direction	2	3434.581	100.011	p < .001
Target by Trig by Direction by Consonant	1	3434.123	97.345	p < .001
Trig by Time Point by Direction by Consonant	2	3434.044	19.843	p < .001
Target by Time Point by Direction by Consonant	1	3434.081	12.287	p < .001
Target by Trig by Time Point by Consonant	2	3434.055	34.911	p < .001
Target by Trig by Time Point by Direction by Consonant	3	3434.046	7.131	p < .001

Chapter 3: Tatar, continued

F2 Magnitude Model – Trigger /i/ Only

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	32.287	156.713	p < .001
Target	1	1025.239	29.549	p < .001
Direction	1	1024.988	9.062	p = .003
Time Point	1	1024.045	5.81	p = .016
Consonant	1	1024.849	104.66	p < .001
Target by Consonant	1	1024.76	47.313	p < .001
Time Point by Consonant	1	1023.888	49.265	p < .001
Target by Direction	1	1024.958	17.811	p < .001
Target by Time Point	1	1024.127	19.105	p < .001
Time Point by Direction	1	1024.049	64.483	p < .001
Time Point by Direction by Consonant	2	1024.125	21.139	p < .001
Target by Time Point by Direction	1	1023.955	21.136	p < .001

Chapter 4: Hungarian

F1 Magnitude Model

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	14.176	11.742	p = .004
Target	1	29.895	1.751	p = .196
Trig	2	23.273	9.54	p = .001
Direction	1	197.223	37.417	p < .001
Time Point	1	7171.123	384.265	p < .001
Consonant	2	13.944	54.259	p < .001
Target by Consonant	2	29.916	11.088	p < .001
Trig by Consonant	4	23.285	12.708	p < .001
Direction by Consonant	2	197.38	5.238	p = .006
Time Point by Consonant	2	7166.963	36.628	p < .001
Trig by Direction	2	39.337	12.061	p < .001
Target by Trig	2	15.501	8.304	p = .004
Target by Direction	1	29.894	34.237	p < .001
Target by Time Point	1	7166.919	11.564	p = 0.001
Trig by Time Point	2	7166.86	176.75	p < .001
Time Point by Direction	1	7167.096	46.08	p < .001
Target by Trig by Consonant	4	15.517	5.468	p = .006
Target by Time Point by Consonant	2	7166.857	10.545	p < .001
Trig by Direction by Consonant	4	39.377	3.981	p = .008
Trig by Time Point by Consonant	4	7166.999	11.77	p < .001
Time Point by Direction by Consonant	2	7166.908	6.208	p = .002
Trig by Time Point by Direction	2	7167.018	43.087	p < .001
Target by Trig by Time Point	2	7166.86	64.101	p < .001
Target by Trig by Time Point by Direction	3	7166.981	28.507	p < .001
Target by Trig by Direction by Consonant	6	43.689	3.275	p = .01
Trig by Time Point by Direction by Consonant	4	7166.921	6.3	p < .001
Target by Trig by Time Point by Consonant	4	7167.013	4.485	p = .001
Target by Trig by Time Point by Direction by Consonant	6	7166.972	3.173	p = .004

Chapter 4: Hungarian, continued

F2 Magnitude Model

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	24.148	23.302	p < .001
Target	1	16.987	3.626	p = .074
Trig	2	16.53	10.396	p = .001
Direction	1	24.959	0.06	p = .809
Time Point	1	7184.949	127.164	p < .001
Consonant	2	15.577	64.306	p < .001
Target by Consonant	2	16.989	18.175	p < .001
Trig by Consonant	4	16.531	32.755	p < .001
Time Point by Consonant	2	7175.002	137.216	p < .001
Target by Trig	2	16.054	12.336	p = .001
Target by Direction	1	16.985	17.602	p = .001
Target by Time Point	1	7175.003	342.037	p < .001
Trig by Time Point	2	7174.988	7.846	p < .001
Time Point by Direction	1	7175.04	5.558	p = .018
Target by Trig by Consonant	4	16.055	19.167	p < .001
Target by Time Point by Consonant	2	7174.986	4.577	p = .01
Trig by Time Point by Consonant	4	7175.015	75.444	p < .001
Target by Trig by Time Point	2	7174.985	31.777	p < .001
Target by Trig by Direction	2	31.89	18.837	p < .001
Target by Trig by Direction by Consonant	6	24.448	11.005	p < .001
Trig by Time Point by Direction by Consonant	8	7175.003	2.21	p = .024
Target by Trig by Time Point by Consonant	4	7175.013	76.319	p < .001

APPENDIX D. STATISTICAL CODE

All code provided was written in SPSS v. 25.0.

Chapter 2: Spanish

Anticipatory, Carryover Models at Vowel Edge, Midpoint

Code for four models identical aside from differing subsets

```
MIXED F2 BY Subject Stress Trigger Target
  /CRITERIA=CIN(95) MXITER(100) MXSTEP(10) SCORING(1)
SINGULAR(0.000000000001) HCONVERGE(0, ABSOLUTE) LCONVERGE(0, ABSOLUTE)
PCONVERGE(0.000001, ABSOLUTE)
  /FIXED=Stress Target Trigger Target*Trigger Stress*Trigger
Target*Stress*Trigger | SSTYPE(3)
  /METHOD=REML
  /PRINT=G  R SOLUTION TESTCOV
  /RANDOM=Subject | COVTYPE(VC)
/EMMEANS=TABLES(Stress) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Trigger) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Stress*Trigger) COMPARE(Stress) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Stress*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/SAVE PRED RESID.
```

Magnitude Model

```
MIXED F2Diff BY Subject Stress Trigger TimePoint Direction Consonant
 /CRITERIA=CIN(95) MXITER(100) MXSTEP(10) SCORING(1) SINGULAR(0.000000000001)
HCONVERGE(0, ABSOLUTE) LCONVERGE(0, ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
 /FIXED=Stress Trigger Direction TimePoint Consonant Stress*Consonant
Trigger*Consonant Direction*Consonant TimePoint*Consonant Trigger*Direction
Stress*Trigger Stress*Direction Trigger*TimePoint Direction*TimePoint
  Trigger* Stress*Direction  Stress*Trigger*Consonant
Trigger*Direction*Consonant Trigger*TimePoint*Consonant  | SSTYPE(3)
 /METHOD=REML
 /PRINT=G R SOLUTION TESTCOV
 /RANDOM=INTERCEPT | SUBJECT(Subject) COVTYPE(VC)
/EMMEANS=TABLES(TimePoint) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Consonant) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Stress) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Stress*Consonant) COMPARE(Stress) ADJ(BONFERRONI)
/EMMEANS=TABLES(Stress*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Stress*Consonant) COMPARE(Stress) ADJ(BONFERRONI)
/EMMEANS=TABLES(Stress*Consonant) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Consonant) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction*Consonant) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Consonant*TimePoint) COMPARE(TimePoint) ADJ(BONFERRONI)
```

```
/EMMEANS=TABLES(Consonant*TimePoint) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Direction) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Direction) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Stress*Direction) COMPARE(Stress) ADJ(BONFERRONI)
/EMMEANS=TABLES(Stress*Direction) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*TimePoint) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*TimePoint) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction*TimePoint) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction*TimePoint) COMPARE(Direction) ADJ(BONFERRONI).
```

Chapter 3: Tatar

F1, F2 Models at Vowel Edge, Midpoint

Code for four models identical aside from differing dependent variable and subset

```
MIXED F1 BY Subject Consonant Direction Target Trigger
  /CRITERIA=CIN(95) MXITER(100) MXSTEP(10) SCORING(1)
SINGULAR(0.000000000001) HCONVERGE(0, ABSOLUTE) LCONVERGE(0, ABSOLUTE)
PCONVERGE(0.000001, ABSOLUTE)
  /FIXED=Target Trigger Consonant Direction Target*Trigger
Target*Consonant*Trigger Target*Direction*Trigger
Target*Consonant*Direction*Trigger | SSTYPE(3)
  /METHOD=REML
  /PRINT=G  R SOLUTION TESTCOV CPS DESCRIPTIVES
/RANDOM=INTERCEPT  | SUBJECT(Subject) COVTYPE(VC)
/EMMEANS=TABLES(Consonant) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Direction*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant*Direction*Trigger) COMPARE(Trigger)
ADJ(BONFERRONI)
/SAVE PRED RESID.
```

F1 Magnitude Model

```
MIXED F1Diff BY Subject Target Trigger TimePoint Direction Consonant
 /CRITERIA=CIN(95) MXITER(100) MXSTEP(10) SCORING(1) SINGULAR(0.000000000001)
HCONVERGE(0, ABSOLUTE) LCONVERGE(0, ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
 /FIXED=Target Trigger Direction TimePoint Consonant Target*Consonant
Trigger*Consonant Direction*Consonant TimePoint*Consonant Trigger*Direction
Target*Trigger Target*Direction Target*TimePoint Trigger*TimePoint
Direction*TimePoint
 Trigger*Direction*Consonant Trigger*TimePoint*Consonant
Direction*TimePoint*Consonant
Trigger*Direction*TimePoint Target*Trigger*TimePoint Trigger*Target*Direction
Target*Trigger*Direction*TimePoint Target*Trigger*Direction*Consonant
Target*Direction*TimePoint*Consonant | SSTYPE(3)
 /METHOD=REML
 /PRINT=G R SOLUTION TESTCOV
 /RANDOM=INTERCEPT | SUBJECT(Subject) COVTYPE(VC)
 /EMMEANS=TABLES(Target) COMPARE ADJ(BONFERRONI)
```

```
 /EMMEANS=TABLES(Trigger) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Consonant) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Consonant) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction*Consonant) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Consonant) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Direction) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Direction) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Target) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Target) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Direction) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Direction) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Target) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Target) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Trigger) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Direction) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Direction) COMPARE(Direction) ADJ(BONFERRONI).
```

F2 Magnitude Model

```
MIXED F2Diff BY Subject Item Target Trigger TimePoint Direction Consonant
 /CRITERIA=CIN(95) MXITER(100) MXSTEP(10) SCORING(1) SINGULAR(0.000000000001)
HCONVERGE(0, ABSOLUTE) LCONVERGE(0, ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
 /FIXED=Target Trigger Direction TimePoint Consonant Target*Consonant
Trigger*Consonant Direction*Consonant TimePoint*Consonant Trigger*Direction
Target*Trigger Target*Direction Trigger*TimePoint Direction*TimePoint
 Target*Direction*Consonant Target*TimePoint*Consonant
Trigger*Direction*Consonant Direction*TimePoint*Consonant
Trigger*Direction*TimePoint Target*Trigger*TimePoint
Target*Direction*TimePoint Trigger*Target*Direction
 Target*Trigger*Direction*Consonant Trigger*Direction*TimePoint*Consonant
Target*Direction*TimePoint*Consonant Target*Trigger*TimePoint*Consonant
Target*Trigger*Direction*TimePoint*Consonant | SSTYPE(3)
 /METHOD=REML
 /PRINT=G R SOLUTION TESTCOV
 /RANDOM=INTERCEPT | SUBJECT(Subject) COVTYPE(VC)
 /EMMEANS=TABLES(Target) COMPARE ADJ(BONFERRONI)
 /EMMEANS=TABLES(Trigger) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Consonant) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Consonant) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction*Consonant) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Consonant) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
```

```
/EMMEANS=TABLES(Trigger*Direction) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Direction) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Target) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Target) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Direction) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Direction) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Direction) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Direction) COMPARE(Direction) ADJ(BONFERRONI).
```

Limited F2 Magnitude Model

```
MIXED F2Diff BY Subject Item Target TimePoint Direction Consonant
 /CRITERIA=CIN(95) MXITER(100) MXSTEP(10) SCORING(1) SINGULAR(0.000000000001)
HCONVERGE(0, ABSOLUTE) LCONVERGE(0, ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
 /FIXED=Target Direction TimePoint Consonant Target*Consonant
TimePoint*Consonant Target*Direction Target*TimePoint Direction*TimePoint
 Direction*TimePoint*Consonant Target*Direction*TimePoint  | SSTYPE(3)
 /METHOD=REML
 /PRINT=G R SOLUTION TESTCOV
 /RANDOM=INTERCEPT | SUBJECT(Subject) COVTYPE(VC)
 /EMMEANS=TABLES(Target) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Consonant) COMPARE ADJ(BONFERRONI).
```

Chapter 4: Hungarian

F1, F2 Models at Vowel Edge, Midpoint

Code for four models identical aside from differing dependent variable and subset

```
MIXED F1 BY Subject Consonant Direction Target Trigger
  /CRITERIA=CIN(95) MXITER(100) MXSTEP(10) SCORING(1)
SINGULAR(0.000000000001) HCONVERGE(0, ABSOLUTE) LCONVERGE(0, ABSOLUTE)
PCONVERGE(0.000001, ABSOLUTE)
  /FIXED=Target Trigger Consonant Direction Target*Trigger
Target*Consonant*Trigger Target*Direction*Trigger
Target*Consonant*Direction*Trigger | SSTYPE(3)
  /METHOD=REML
  /PRINT=G  R SOLUTION TESTCOV CPS DESCRIPTIVES
/RANDOM=INTERCEPT  | SUBJECT(Subject) COVTYPE(VC)
/EMMEANS=TABLES(Consonant) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Direction*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant*Direction*Trigger) COMPARE(Trigger)
ADJ(BONFERRONI)
/SAVE PRED RESID.
```

F1 Magnitude Model

```
MIXED F1Diff BY Subject Item Target Trigger TimePoint Direction Consonant
 /CRITERIA=CIN(95) MXITER(100) MXSTEP(10) SCORING(1) SINGULAR(0.000000000001)
HCONVERGE(0, ABSOLUTE) LCONVERGE(0, ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
 /FIXED=Target Trigger Direction TimePoint Consonant Target*Consonant
Trigger*Consonant Direction*Consonant TimePoint*Consonant Trigger*Direction
Target*Trigger Target*Direction Target*TimePoint Trigger*TimePoint
Direction*TimePoint
 Target*Trigger*Consonant Target*TimePoint*Consonant
Trigger*Direction*Consonant Trigger*TimePoint*Consonant
Direction*TimePoint*Consonant
Trigger*Direction*TimePoint Target*Trigger*TimePoint
Target*Trigger*Direction*TimePoint Target*Trigger*Direction*Consonant
Trigger*Direction*TimePoint*Consonant Target*Trigger*TimePoint*Consonant
Target*Trigger*Direction*TimePoint*Consonant | SSTYPE(3)
 /METHOD=REML
 /PRINT=G R SOLUTION TESTCOV
 /RANDOM=INTERCEPT | SUBJECT(Subject) COVTYPE(VC)
 /RANDOM=INTERCEPT | SUBJECT(Item) COVTYPE(VC)
 /EMMEANS=TABLES(Target) COMPARE ADJ(BONFERRONI)
 /EMMEANS=TABLES(Trigger) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Consonant) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Consonant) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction*Consonant) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Consonant) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Direction) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Direction) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Target) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Target) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Direction) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Direction) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Target) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Target) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Trigger) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Direction) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Direction) COMPARE(Direction) ADJ(BONFERRONI).
```

F2 Magnitude Model

```
MIXED F2Diff BY Subject Item Target Trigger TimePoint Direction Consonant
 /CRITERIA=CIN(95) MXITER(100) MXSTEP(10) SCORING(1) SINGULAR(0.000000000001)
HCONVERGE(0, ABSOLUTE) LCONVERGE(0, ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
 /FIXED=Target Trigger Direction TimePoint Consonant Target*Consonant
Trigger*Consonant TimePoint*Consonant Target*Trigger Target*Direction
Target*TimePoint Trigger*TimePoint Direction*TimePoint
```

```
 Target*Trigger*Consonant Target*TimePoint*Consonant
Trigger*TimePoint*Consonant
Target*Trigger*TimePoint Trigger*Target*Direction
Target*Trigger*Direction*Consonant Trigger*Direction*TimePoint*Consonant
Target*Trigger*TimePoint*Consonant | SSTYPE(3)
 /METHOD=REML
 /PRINT=G R SOLUTION TESTCOV
 /RANDOM=INTERCEPT | SUBJECT(Subject) COVTYPE(VC)
 /RANDOM=INTERCEPT | SUBJECT(Item) COVTYPE(VC)
/EMMEANS=TABLES(TimePoint) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Target) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Direction) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(Consonant) COMPARE ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Consonant) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Target) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Target) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Trigger) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Trigger) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Direction) COMPARE(TimePoint) ADJ(BONFERRONI)
/EMMEANS=TABLES(TimePoint*Direction) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Consonant) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Consonant) COMPARE(Consonant) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Target) COMPARE(Trigger) ADJ(BONFERRONI)
/EMMEANS=TABLES(Trigger*Target) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Direction) COMPARE(Target) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Direction) COMPARE(Direction) ADJ(BONFERRONI)
/EMMEANS=TABLES(Target*Trigger*Direction*Consonant) COMPARE(Direction)
ADJ(BONFERRONI).
```