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Vowel-to-Vowel Coarticulation in Spanish Nonwords

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Abstract

The present study examined vowel-to-vowel (VV) coarticulation in backness affecting mid vowels /e/ and /o/ in 36 Spanish nonwords produced by 20 native speakers of Spanish, aged 19–50 years (mean = 30.7; SD = 8.2). Examination of second formant frequency showed substantial carryover coarticulation throughout the data set, while anticipatory coarticulation was minimal and of shorter duration. Furthermore, the effect of stress on vowel-to-vowel coarticulation was investigated and found to vary by direction. In the anticipatory direction, small coarticulatory changes were relatively stable regardless of stress, particularly for target /e/, while in the carryover direction, a hierarchy of stress emerged wherein the greatest coarticulation occurred between stressed triggers and unstressed targets, less coarticulation was observed between unstressed triggers and unstressed targets, and the least coarticulation occurred between unstressed triggers with stressed targets. The results of the study augment and refine previously available knowledge about vowel-to-vowel coarticulation in Spanish and expand cross-linguistic understanding of the effect of stress on the magnitude and direction of vowel-to-vowel coarticulation.

1 Introduction

When the articulation of a speech sound undergoes alteration as a result of the proximity of a neighboring segment, the resultant changes are known as coarticulation. Coarticulation has been documented for a vast variety of languages and is an inherent property of speech, facilitating efficient speech production (Lindblom & MacNeilage, 2011) and allowing listeners to anticipate upcoming phonemic material as speech unfolds in time (Beddor, Harnsberger, & Lindemann, 2002). Given this universality and the central role that coarticulation plays in both speech production and perception, it is important to identify the factors that affect the nature and magnitude of coarticulation. In the

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domain of vowel-to-vowel (VV) coarticulation, previous research has addressed the influence of intervening consonants, vowel identity, and the role of stress, among other factors, albeit often separately. We build on these studies by analyzing the combined effects of stress, target vowel, and trigger vowel on VV coarticulation in Spanish-like nonwords, 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 fall on any syllable in trisyllabic words, and in longer words can also appear prior to the antepenult. When stress falls anywhere but the penultimate syllable, it is communicated orthographically by the acute accent mark, making possible the use of carefully designed nonwords with predetermined stress assignment.

Experimental investigations of speech phenomena, including coarticulation, typically limit their focus to one or two factors of interest, though it is understood that multiple factors can be at work simultaneously. The present study aims to contribute to the field of speech research by beginning to address the role of multiple interconnected factors, focusing on the domain of VV coarticulation. The results of this study also have methodological implications, highlighting factors to take into account in designing studies involving coarticulation. While previous research has addressed the roles of stress, vowel and consonant identity, and direction in coarticulation, few studies have investigated their combined effects. One of the specific contributions of the present research is that it examines the effect of stress in combination with that of other factors. This methodology allows us to pit the strength of individual factors against each other and determine whether the effect of one factor is conditional on the influence of another. This study is also one of the first investigations of Spanish coarticulation to present data from a broad sample of speakers. For example, Recasens's (1987) study examined 2 speakers of Spanish, while Henriksen (2017) reported only on anticipatory assimilation from 24 speakers. The present study 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 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. In this introduction, we 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.

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., Fowler, 1981, Magen, 1984, Magen, 1997, Beddor et al., 2002, and Majors, 2006, on English; Mok, 2013, on Mandarin and Cantonese;

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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 2 out of 4 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 et al. (2002) found stress asymmetries in VV coarticulation in English (a nontonal, stress-timed language), but not in Shona (a Bantu language with lexical tone), while Manuel and 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., Recasens, 1987; Beddor & Yavuz, 1995; Nicolaidis, 1999; Majors, 2006) 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 (since the two factors are conflated in such designs). 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 separated from the effects of stress-dependent qualitative reduction. Building on previous research, the stimuli 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.

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. Nonlingual consonants, such as /p/ and /b/, have generally been found to permit a large degree of VV coarticulation (Fowler & Brancazio,

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2000; Modarresi, Sussmann, Lindblom, & Burlingame, 2004), while lingual consonants have often been shown to reduce VV coarticulatory effects. Some studies also 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, such 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 in the degree of VV coarticulation that particular sequences will allow can be expected across languages (Recasens, Farnetani, Fontdevila, & Pallarès, 1993; Modarresi et al., 2004). In the present study, we are 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. (Since only these two consonants were included in the current study, the role of intervening consonant identity is not examined.) 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.

1.3 Effect of Vowel Identity 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 (Butcher & Weiher, 1976; Beddor & Yavuz, 1995), but a correspondingly poor target (Recasens, 1987; Majors, 2006). Low vowels, on the other hand, have been shown to undergo coarticulation without causing it (see, e.g., Recasens, 1987; Beddor & Yavuz, 1995; Mok, 2011; Recasens, 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. The present study 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.

1.4 Direction of Coarticulation

VV coarticulation can proceed in two different directions: anticipatory, occurring when a preceding vowel assimilates to a following one, and carryover, when a following vowel assimilates to a preceding one. Fundamentally different

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mechanisms are believed to underlie the two directions of coarticulation. Carryover coarticulation is 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 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., Bell-Berti & Harris, 1976; Manuel & Krakow, 1984; Beddor et al., 2002), while stronger anticipatory effects have been found in many other languages, including Shona (Manuel & Krakow, 1984; Beddor et al., 2002), Swahili (Manuel & Krakow, 1984), Tatar (Conklin, 2015), and Turkish (Beddor & Yavuz, 1995). In the one study that has examined VV coarticulation in Spanish in both directions (Recasens, 1987), neither direction emerged as clearly dominant. The causes of these cross-linguistic differences are not fully understood, although one potentially explanatory factor is the location of stress, particularly 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. (This factor has been proposed to be one of the central drivers of direction of VV coarticulation in languages such as Turkish (Beddor & Yavuz, 1995) and Tatar (Conklin, 2015).) Additionally, consonantal restrictions on tongue-dorsum movements associated with particular segments can block or facilitate coarticulation in a particular direction (Recasens, Pallarès, & Fontdevila, 1997; Recasens, 2002). Intervening dorsal consonants and other segments specifying tongue body gestures generally reduce anticipatory VV coarticulation (Recasens, 1999b), though we are not aware of any typological analysis linking language-specific preferences in VV coarticulatory direction across all possible intervening consonants to the consonantal phoneme inventory and its corresponding directional preferences. Thus, stress, vowel and consonant inventories, and the language-specific phonetic properties of individual segments may guide the general coarticulatory trends of a language, along with more controversial factors such as vowel inventory density, language-specific phonemic contrasts discouraging certain coarticulatory variation, and the presence or absence of vowel harmony (Manuel, 1999). The interaction of these factors jointly shapes patterns of VV coarticulation. The present study recognizes the fact that VV coarticulation is a complex process involving simultaneous contributions by multiple factors and aims to examine in a systematic fashion their joint effect on VV coarticulation in Spanish – a language particularly suited for exploration of this type.

1.5 Spanish and Its Vowel System

Spanish was chosen as the target language for the present study due to several convenient properties of its phonological system. First, Spanish vowels do not undergo the extensive phonetic reduction in unstressed positions that char-

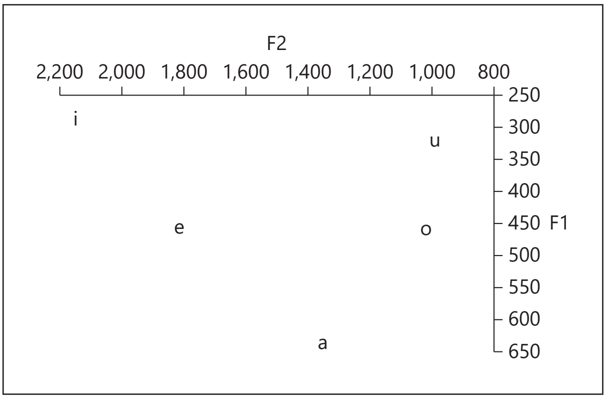

Fig. 1. Spanish vowel space (based on formant values reported in Bradlow (1995, p. 1918)).

acterizes 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 4 male speakers of Madrid Spanish (represented in Fig. 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.

1.6 The Present Study

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. It relies on specially designed sets of Spanish-like nonwords that vary minimally with regard to each factor. To test the hypothesis that stressed vowels are more resistant to coarticulation than unstressed ones, the study compares the coarticulatory results of all phonologically possible combinations of stressed and unstressed trigger vowels with stressed and unstressed target vowels. This design also allowed us to address an additional question: whether stressed vowels are better triggers of coarticulation than unstressed ones. By using 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 in disyllables without making this distinction (Recasens, 1987; Beddor & Yavuz, 1995; Nicolaidis, 1999; Majors, 2006).

To assess coarticulatory differences in each of the conditions listed above, we analyzed the second formant frequency (F2) of target vowels in the speech of 20 native speakers of Spanish. Due to this relatively large sample size, this study has the benefit of capturing a wide cross-section of the coarticulatory vari-

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ation present in the general population and minimizing the impact of subject-related variability. In the next section, we 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 Materials and Methods

2.1 Participants

Twenty native Spanish speakers (F = 12; M = 8) aged 19–50 years (mean = 30.7; SD = 8.2) completed the study; 13 participants were from Colombia, 3 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 5-vowel inventory with similar overall spacing (Canfield, 1981; Lipski, 1994; Chládková, Escudero, & Boersma, 2011; Vera Diettes, 2014; Dabkowski, 2018; Holliday & Martin, 2018), it enhances the generalizability of the results.[1] Given that the study was conducted in the USA, all participants were bilingual in English and all resided in the USA 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 anticipate.

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 Stimuli

Target items and fillers were three-syllable Spanish-like nonwords with stress on the first, second, or third syllable of the word, listed in Appendix A. (Each stimulus 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. 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 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, /ke'keke/ or /po'popo/ (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, /ko'keke/ creates the conditions needed for the carryover effect of unstressed /o/ (V_1) on stressed /e/ (V_2) when compared to /ke'keke/, while /ke'keko/ creates the conditions for the anticipatory effect of un-

[1] One participant came from Mexico City, Mexico, an area that has been noted to exhibit reduction and variation in unstressed vowels (Lipski, 1994; Dabkowski, 2018). 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, it was judged that there was not sufficient reason to exclude the participant, and their data were included in the analysis.

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stressed /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. /ko'keke/), the effect of a stressed trigger on an unstressed target, (e.g. /'kokeke/), and the effect of an unstressed trigger on an unstressed target, (e.g. /koke'ke/), in both the anticipatory and carryover directions for a total of 36 stimuli (3 trigger types (preceding, following, canonical) × 2 target vowels × 2 consonantal environments × 3 stress locations). Additionally, 84 fillers were included as distractor items. All stimuli and fillers were read 3 times. Thus, each subject read a total of 360 sentences.

2.3 Procedure

Participants completed a language background questionnaire and a production task in which they read nonwords embedded in 10 carrier phrases, as shown:

Quien ganó el _____ por la mañana fue Carlos.

It was Carlos who won the ________ this morning.

Carrier phrases were randomized across trials. (All 10 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 nonword items at a 1:2.3 ratio. Fillers, like targets, were 3-syllable, Spanish-like nonwords, but exhibited greater phonological variety than the target words. One hundred eight target tokens were presented to each participant. Participants were informed that stress would be marked in relatively unusual positions on the nonwords (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 after annotation for similar reasons, for a total of 423 excluded items. To verify the researcher's judgments about the location of stress, 3 linear mixed model analyses were computed with vowel duration, vowel f0 at midpoint, and vowel intensity at midpoint as the dependent variables, stress (stressed vs. unstressed) and inclusion (included in analysis vs. 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 after annotation. The interaction between stress and inclusion was significant in each model ($F(1, 1{,}932.650) = 16.501$, $p < 0.001$ for f0, $F(1, 1{,}944.655) = 10.432$, $p < 0.01$ for intensity, and $F(1, 1{,}945.553) = 285.815$, $p < 0.001$ 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 ($n = 1{,}737$), but not those excluded ($n = 228$). Duration differentiated stress for both included and excluded utterances (Table 1), but the difference in means was notably greater 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 the researcher's judgment.

Because a relatively high rate of data loss occurred due to stress misallocation, a structural change to the procedure was made after 9 participants. While the first 9 participants encountered stimuli with stress on any of 3 syllables within the same block, the remaining 11 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.

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Table 1. Mean duration (ms) of stressed and unstressed vowels relative to inclusion in analysis

	Included	Excluded
Stressed	93.3	69.6
Unstressed	59.9	74.6
Difference	33.4	–5.0

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 at the researcher's university 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 min, and breaks were offered every 40 sentences to prevent fatigue effects.

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%). (For alternative approaches to acoustic analysis of coarticulation, see Recasens (1999a).) F2 measurements were used to assess coarticulation in backness, and F1 measurements were used to normalize F2 values. The LPC measurements were checked visually by a researcher; 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, 2018). Log-additive regression normalization was chosen because it was designed for data sets with missing and unbalanced data, such as this study. Unlike many vowel-extrinsic methods, this approach can be implemented using a subset of a language's vowel inventory, provided the data set contains productions of all represented phonemes from each speaker (Barreda & Nearey, 2018), and initial exploratory analyses suggested that it is more successful at preserving coarticulatory variation than the Bark method (see, e.g., Traunmüller, 1990).

2.5 Analysis

Linear mixed models comparing coarticulated and canonical target words (e.g., /ko'keke/ and /ke'keke/, respectively) were used to detect VV coarticulation and the impact of stress on coarticulation (implemented in SPSS 25, IBM Corp., 2017). This approach allowed us to detect the presence of significant coarticulation, setting the present study apart from previous investigations, which often used statistical approaches that limited their conclusions to the comparable magnitude of coarticulatory tendencies across conditions. By contrast, the current study documents whether coarticulation occurs regularly and reliably in each condition.

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. 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 a proxy for the difference in backness (and concomitant rounding) between canonical and coarticulated vowels. The acoustic analysis undertaken here does not differentiate between coarticulation in backness and coarticulation in rounding, nor distinguish the distinct articulatory sources of these features (the tongue body and lips, respectively). However, the examination of F2 as a shared acoustic cue for both features reflects the phonological organization of the Spanish vowel system, where backness and rounding always covary for nonlow vowels, as well as the acoustic collapse of distinct articulatory gestures into a shared acoustic cue. Thus, the acoustic coarticulation examined herein through a single acoustic parameter can be attributed to at least two distinct articulatory sources.

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 a 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 greater 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.

A significant two-way target by trigger interaction would indicate that the magnitude of coarticulation differs by trigger-target pair (/e/ affecting /o/ vs. /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.

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. Canonical words with second-syllable stress, like /ke'keke/, would need to serve simultaneously as controls for anticipatory targets like /ke'keko/ and carryover targets like /ko'keke/, creating serious difficulties in data analysis and the interpretation of results. Finally, models were separated by time point in order to facilitate model convergence.

3 Results

Results are reported by model, beginning with the models describing anticipatory coarticulation (at vowel edge and vowel midpoint), followed by carryover models for each time point. Section 3.1 examines the impact of the change in blocking procedure presented in 2.3. Section 3.2 presents the results related to anticipatory coarticulation. Section 3.3 examines carryover coarticulation. Section 3.4 summarizes the effects discussed in previous sections. All post hoc analyses were conducted with Bonferroni correction.

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 section 2.3), each model was computed separately on each of 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

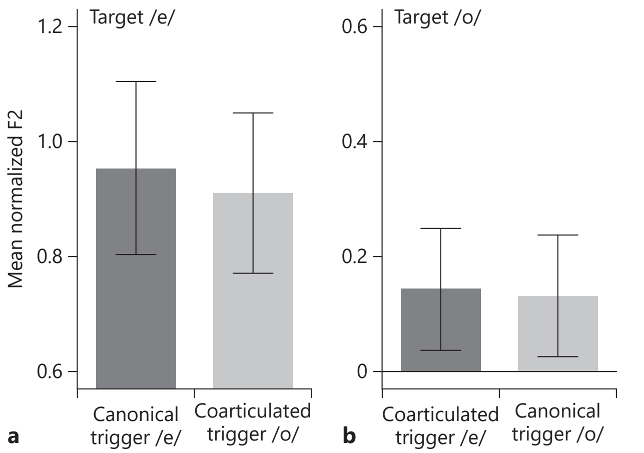

Fig. 2. Mean normalized F2 by target and trigger for the anticipatory model at vowel edge. The difference between the two bars of each panel shows the average magnitude of coarticulation. Coarticulated vowels appear when the target and trigger are identical (the rightmost bar in **a** and leftmost in **b**). The two *y* axes are set to the same scale, but a different range, in order to visually enhance coarticulation; this adjustment reduces the visual difference in backness across target vowels. Error bars display 1 standard deviation above and below the mean.

therefore less power, no new coarticulatory trends emerged. Therefore, we concluded that the change to the blocking procedure did not have a substantial impact on the results and proceeded to report the data from all subjects together. All results presented in this section are from models including all 20 participants, with no separation between subjects based on blocking procedure.

3.2 Anticipatory Coarticulation

3.2.1 At Vowel Edge

In the model for anticipatory coarticulation at vowel edge, significant main effects were present for stress ($F(2, 1{,}158.901) = 3.810$, $p < 0.05$), target ($F(1, 1{,}149.919) = 12{,}344.828$, $p < 0.001$), and trigger ($F(1, 1{,}150.221) = 25.527$, $p < 0.001$). While the effect of stress and target demonstrates the impact of stress and vowel identity on vowel acoustics, 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 ($F(1, 1{,}150.072) = 0.252$, $p = 0.616$), which indicates that no difference in the magnitude of coarticulation was detected across target vowels (Fig. 2).

In addition to detecting coarticulation between /e/ and /o/, our primary interest is in distinguishing differences in the degree of coarticulation under differing conditions of stress. By using trisyllabic stimuli, we tested three stress

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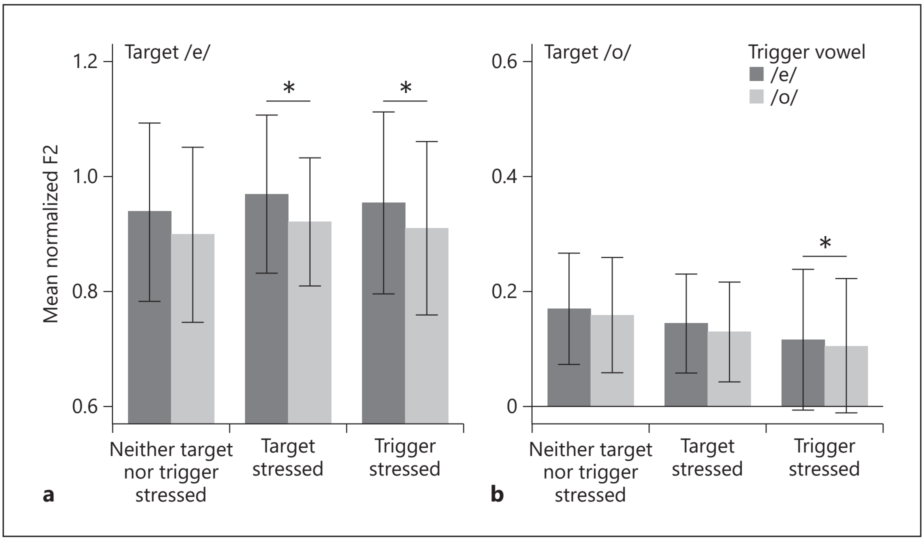

Fig. 3. a Target /e/. **b** Target /o/. Mean normalized F2 by stress and trigger for the anticipatory model at vowel edge. The difference between the dark and light bars shows the average magnitude of coarticulation. Error bars display 1 standard deviation above and below the mean. The two *y* axes are set to the same scale, but a different range, in order to visually enhance coarticulation; this adjustment reduces the visual difference in backness across target vowels. * $p < 0.05$.

conditions: stress fell on the target vowel (V2), the trigger vowel (for anticipatory coarticulation, V3), or the unchanging third syllable, referred to as "neither trigger nor target stressed" (for anticipatory coarticulation, V1). The two-way interaction between stress and trigger was not significant ($F(2, 1{,}148.946) = 0.111$, $p = 0.895$). The three-way interaction between stress, target, and trigger was significant ($F(4, 1{,}150.391) = 4.712$, $p < 0.01$), 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 comparisons with Bonferroni correction showed significant or near-significant coarticulation for target /e/ under all three conditions of stress, though the difference of means, indicating the magnitude of coarticulation, was slightly greater when stress fell on the target vowel (0.044) or trigger vowel (0.043) than the unchanging first syllable (0.034). For target /o/, significant coarticulation was detected only in the trigger stressed condition. The differences in means are depicted graphically in Figure 3 and numerically in Table 2. These results suggest that the location of stress did not make a strong impact on anticipatory coarticulation in /e/, but did for anticipatory coarticulation in /o/, which was conditional on the stressed trigger.

3.2.2 At Vowel Midpoint

The results of the model for anticipatory coarticulation at vowel midpoint showed a significant main effect for stress ($F(2, 1{,}157.003) = 9.818$, $p < 0.001$) and

Table 2. Post hoc results of stress by target vowel by trigger vowel interaction for anticipatory coarticulation at vowel edge

Target vowel	Stress	Significance: *p* value	Difference in means
Target /e/	Target stressed	<0.05	0.044
	Trigger stressed	<0.05	0.043
	Neither stressed	ns (p = 0.0504)	0.034
Target /o/	Target stressed	ns (p = 0.064)	0.035
	Trigger stressed	<0.05	0.034
	Neither stressed	ns (p = 0.094)	0.030

ns, not significant.

Table 3. Post hoc results of stress by target vowel by trigger vowel interaction for anticipatory coarticulation at vowel midpoint

Target vowel	Stress	Significance	Difference in means
Target /e/	Target stressed	ns	0.005
	Trigger stressed	ns	0.016
	Neither stressed	ns	0.004
Target /o/	Target stressed	ns	0.018
	Trigger stressed	ns	0.001
	Neither stressed	ns	0.001

ns, not significant.

target (F(1, 1,150.323) = 18,557.360, p < 0.001), but not for trigger (F(1, 1,150.589) = 0.065, p = 0.798). This lack of trigger significance indicates that, generally, VV coarticulatory effects in the anticipatory direction did not extend to vowel midpoint. The interaction between target vowel and trigger vowel was not significant either (F(1, 1,150.377) = 1.348, p = 0.246), nor was the stress by trigger vowel interaction (F(2, 1,149.703) = 0.528, p = 0.590); however, the three-way interaction between stress, target vowel, and trigger vowel was significant (F(4, 1,150.627) = 4.896, p < 0.01). Nevertheless, the post hoc analyses testing for coarticulation in each combination of stress and target levels yielded no significant results (Table 3). This is consistent with the overall finding that coarticulatory effects did not extend to vowel midpoint in the anticipatory direction.

3.3 Carryover Coarticulation

3.3.1 At Vowel Edge

In the model examining carryover coarticulation at vowel edge, the main effects of stress (F(2, 1,139.946) = 4.696, p < 0.01), target (F(1, 1,127.328) =

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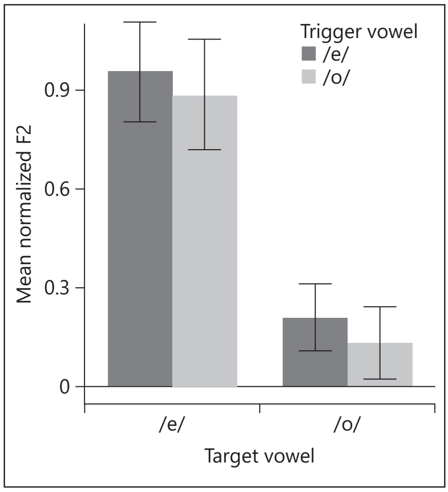

Fig. 4. Mean normalized F2 by target and trigger for the carryover model at vowel edge. Taller bars indicate more frontal vowels. The difference between the dark and light bars shows the average magnitude of coarticulation. Lighter /e/ (rightmost bar in the /e/ cluster) and darker /o/ (leftmost bar in the /o/ cluster) correspond to coarticulated vowels. Error bars display 1 standard deviation above and below the mean.

Table 4. Post hoc results of stress by target by trigger interaction for carryover coarticulation at vowel edge

Target vowel	Stress	Significance: *p* value	Difference in means
Target /e/	Target stressed	<0.01	0.056
	Trigger stressed	<0.001	0.088
	Neither stressed	<0.001	0.08
Target /o/	Target stressed	<0.05	0.047
	Trigger stressed	<0.001	0.079
	Neither stressed	<0.05	0.047

9,657.429, $p < 0.001$) and trigger ($F(1, 1{,}127.792) = 77.151$, $p < 0.001$) were significant, with the effect of trigger indicating the presence of significant coarticulation across the two target vowels /e/ and /o/. The interaction between target and trigger was not significant ($F(1, 1{,}128.571) = 1.255$, $p = 0.263$), suggesting that the magnitude of coarticulation did not differ significantly between targets /e/ and /o/. The differences of means (0.075 for target /e/ and 0.058 for target /o/), displayed in Figure 4, were larger than the differences of means in the 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.

The two-way interaction between stress and trigger was not significant ($F(2, 1{,}127.662) = 1.481$, $p = 0.228$), but the three-way interaction between stress, target, and trigger was ($F(4, 1{,}130.604) = 7.322$, $p < 0.001$), suggesting that the effect of stress on the degree of coarticulation differed by target. Post

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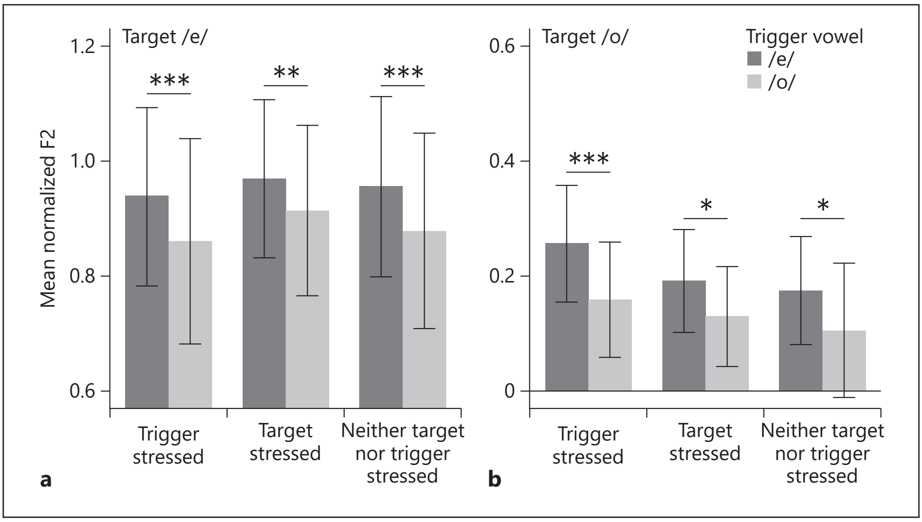

Fig. 5. a Target /e/. **b** Target /o/. Mean normalized F2 by stress and trigger for the carryover model at vowel edge. The difference between the dark and light bars shows the average magnitude of coarticulation. Error bars display 1 standard deviation above and below the mean. The two *y* axes are set to the same scale, but a different range, in order to visually enhance coarticulation; this adjustment reduces the visual difference in backness across target vowels. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

hoc tests found a significant effect of trigger for each combination of target and stress, indicating coarticulation in each case. The differences of means are reported in Table 4.

Examination of the differences in means reported in Table 4 and graphically represented in Figure 5 indicates that coarticulatory effects for both vowels were the strongest when the preceding trigger was stressed, which is especially evident for target /o/. Additionally, for /e/, coarticulation is appreciably weaker when the target itself is stressed. The three-way interaction was likely due to the fact that the target stressed condition demonstrated the weakest coarticulation for target /e/, while for target /o/ this condition did not differ in magnitude from the neither stressed condition.

3.3.2 At Vowel Midpoint

As in the edge model, the main effects of stress ($F(2, 1{,}139.746) = 13.329$, $p < 0.001$), target ($F(1, 1{,}130.521) = 15{,}272.626$, $p < 0.001$), and trigger ($F(1, 1{,}130.879) = 25.739$, $p < 0.001$) were significant for carryover coarticulation at vowel midpoint, and the interaction between target and trigger was not significant ($F(1, 1{,}131.358) = 0.716$, $p = 0.398$), suggesting that, overall, the magnitude of coarticulation was comparable across the two target vowels. Figure 6 displays the mean normalized F2 for each condition of trigger for both target vowels. The results of this model indicate that carryover coarticulation is not limited to the vowel edge closest to the trigger vowel and extends at least to vowel midpoint.

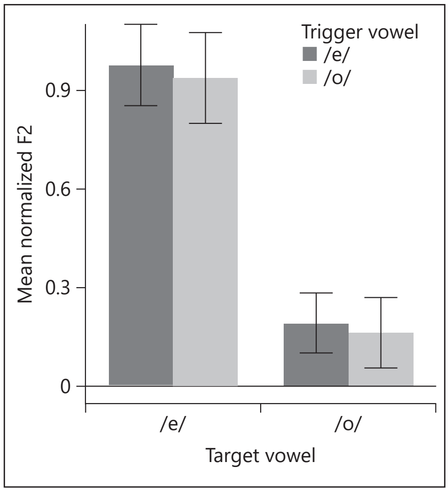

Fig. 6. Mean normalized F2 by target and trigger for the carryover model at vowel midpoint. Taller bars indicate more frontal vowels. The difference between the dark and light bars shows the average magnitude of coarticulation. Lighter /e/ (rightmost bar in the /e/ cluster) and darker /o/ (leftmost bar in the /o/ cluster) correspond to coarticulated vowels. Error bars display 1 standard deviation above and below the mean.

Table 5. Post hoc results of stress by target by trigger interaction for carryover coarticulation at vowel midpoint

Target vowel	Stress	Significance: *p* value	Difference in means
Target /e/	Target stressed	ns	0.009
	Trigger stressed	<0.001	0.054
	Neither stressed	<0.01	0.049
Target /o/	Target stressed	ns	0.022
	Trigger stressed	<0.05	0.035
	Neither stressed	ns	0.023

ns, not significant.

As in the edge model, the two-way interaction between stress and trigger was not significant ($F(2, 1{,}130.802) = 1.675$, $p = 0.188$), while the three-way interaction of stress, trigger, and target was significant ($F(4, 1{,}132.690) = 7.211$, $p < 0.001$), indicating that stress moderated the magnitude of coarticulation in different ways across the two targets. 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 (Table 5). These results suggest that sustained coarticulation in /o/ is conditional on a stressed trigger, while sustained coarticulation in /e/ can occur under more varied stress conditions (in this case, both trigger stressed and neither stressed). The differences in average magnitude of coarticulation across stress conditions and target vowels are displayed visually in Figure 7.

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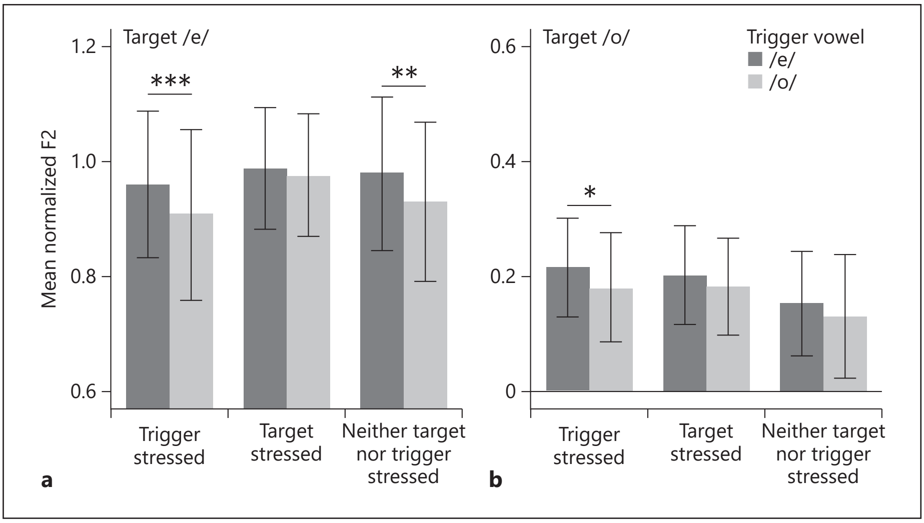

Fig. 7. a Target /e/. **b** Target /o/. Mean normalized F2 by stress and trigger for the carryover model at vowel midpoint. The difference between the dark and light bars shows the average magnitude of coarticulation. Error bars display 1 standard deviation above and below the mean. The two *y* axes are set to the same scale, but a different range, in order to visually enhance coarticulation; this adjustment reduces the visual difference in backness across target vowels. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

3.4 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. Mean differences corresponding to magnitude of coarticulation were also smaller for anticipatory coarticulation than carryover. Furthermore, stress had a role to play in mediating coarticulation in each model, as shown in all four models by a significant three-way interaction between stress, target, and trigger. In all models, the effect of stress on coarticulation was conditional on target vowel. The overall pattern that emerges is that coarticulation in /o/ is often conditional on a stressed trigger, while /e/ coarticulated under more varied stress conditions. Even when significant coarticulation was detected for both vowels under all stress conditions (e.g., carryover vowel edge), the magnitude of coarticulation, indicated by differences in means, was typically greatest when the trigger was stressed. Stressed targets sometimes emerged as the weakest coarticulatory scenario, although with less consistency.

In the anticipatory model for vowel edge, post hoc tests detected significant coarticulation for target /o/ when the trigger was stressed and for target /e/ when either the target or the trigger was stressed. In the anticipatory model at vowel midpoint, the significant three-way interaction was attributable to factors other than differences in coarticulation due to stress.

All stress and target vowel combinations in the carryover model at vowel edge showed significant coarticulation in post hoc analyses, with the greatest magnitudes in the trigger stressed category (for either target vowel). For target /e/, the neither stressed category was second in the magnitude of coarticulation. In these three cases (trigger stressed for targets /e/ and /o/ and neither stressed for target /e/), carryover coarticulation was strong enough to remain significant at vowel midpoint.

In summary, four general trends emerged: (1) significant carryover coarticulation was widespread at vowel edge, persisting in some cases until vowel midpoint; (2) anticipatory coarticulation at vowel edge was found only in some stress conditions and did not persevere until vowel midpoint; (3) stressed triggers intensified coarticulation while stressed targets impeded it; and (4) coarticulation in /o/ was conditional upon the trigger being stressed, while /e/ coarticulated under a wider range of stress conditions.

4 Discussion

4.1 Directional Asymmetries in Coarticulation

The experimental design was successful in detecting 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 mean magnitude, while carryover coarticulation persisted longer and was of a greater mean magnitude (estimated based on the differences of means). This was reflected 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, remaining statistically detectable at midpoint. The difference in means was also greater in the carryover direction (0.066 at vowel edge and 0.032 at midpoint) than the anticipatory (0.036 at vowel edge), indicating that carryover coarticulation had a greater average magnitude. Thus, one of the core findings of the study is that carryover coarticulatory effects are stronger and more stable than anticipatory ones in the contexts examined here. Furthermore, effects with a larger difference in means at vowel edge (greater than 0.06) remained 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 (Bell-Berti & Harris, 1976; Manuel & Krakow, 1984; Beddor et al., 2002), while anticipatory effects are stronger than carryover in Shona, Swahili, Tatar, and Turkish (Manuel & Krakow, 1984; Beddor & Yavuz, 1995; Beddor et al., 2002; Conklin, 2015). 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 we are

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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 over anticipatory coarticulation is the 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. Previous research suggests that L2 learners can acquire native-like coarticulatory patterns in their L2, given sufficient L2 experience (Oh, 2008), though we are not aware of any studies investigating the transfer of L2 coarticulatory patterns to the L1. Nevertheless, other aspects of first language phonetics and phonology, most often the realization of voicing via voice onset time, have been shown to be affected by exposure to a second language (Flege, 1987; Sancier & Fowler, 1997; Chang, 2012). 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.

To summarize, the predominance of carryover 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. Further research is necessary to resolve this issue.

4.2 Effect of Stress on VV Coarticulation

A central goal of this study was to determine whether stressed vowels were more likely to undergo VV coarticulation than unstressed vowels. We 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., Fowler, 1981; Nicolaidis, 1999; Beddor et al., 2002; Majors, 2006; Mok, 2013; Recasens, 2015). Additionally, we 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 we examined. Stressed targets always exhibited the least amount of coarticulation or failed to demonstrate statistically significant coarticulation. The only exception to this behavior was stressed /e/, which was subject to significant coarticulation in the anticipatory direction of a magnitude comparable to that undergone by unstressed /e/. Thus, the prediction that stressed vowels would undergo less VV coarticulation was largely confirmed, though at least one case did not conform to it.

The asymmetry that appeared across the two directions of coarticulation with regard to stress may have a perceptual explanation. In our data, carryover coarticulation had more effects at vowel midpoint and overall larger differences in means, and it conformed to the predicted pattern wherein stressed targets coarticulated less than unstressed ones, while anticipatory coarticulation, at least for target /e/, did not follow this pattern and instead exhibited surprising coarticulation in stressed /e/. Whalen's (1990) work suggested that anticipatory coarticulation plays an important perceptual role in priming the listener to anticipate upcoming information. Similarly, later work by Scarborough (2013) demonstrated that coarticulation increased as lexical familiarity decreased, implying that coarticulation potentially serves some perceptual function, at least in the eyes of the speakers. Given that stressed vowels are likely to have the greatest perceptual salience, anticipatory coarticulation on stressed vowels could provide the greatest perceptual impact in foreshadowing upcoming segments. Thus, the somewhat unexpected anticipatory coarticulation found for stressed /e/ may represent an example of "audience design," an attempt on the part of the speaker to encode the features of the upcoming trigger in the preceding stressed target. The absence of comparable anticipatory coarticulation on stressed /o/ is explained by /o/'s overall lower tendency to coarticulate combined with overall weaker coarticulation in the anticipatory direction.

With regard to the overarching tendency of stressed targets to coarticulate less, we propose that stressed target vowels are more likely than their unstressed counterparts to be hyperarticulated and articulatorily stable. Hyperarticulated segments may involve more pronounced articulatory gestures, longer closures, or tighter constrictions, and in the case of vowels, assume a tighter relationship with the presumed vowel target (de Jong et al., 1993; de Jong, 1995). This dedication to canonical productions naturally discourages extreme VV coarticulation.

The second core question of this study was whether stressed vowels made better or worse triggers of coarticulation. Several studies which showed that stressed syllables coarticulate less used dissyllabic designs. Such designs conflate stressed targets with unstressed triggers. As a result, weaker coarticulation in stressed syllables could be ascribed either to a stressed target or to an unstressed trigger (e.g., Recasens, 1987; Beddor & Yavuz, 1995; Nicolaidis, 1999; Majors, 2006). One study that specifically targeted this question is Cho (2004). Investigating prosodically accented 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. Our data, by contrast, support the claim that stressed vowels are more effective triggers of VV coarticulation in unstressed targets than unstressed triggers are. This discrepancy with 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 stimuli vs. word accent in multisyllabic target words). Our attempt to disambiguate the target stressed and trigger stressed conditions, often conflated in disyllabic designs, found that the greatest coarticulation generally occurred in the trigger stressed condition. This pattern held true in the anticipatory direction for target /o/ and in the carryover direction regardless of target vowel identity. Thus, on the whole, stressed triggers are more effective than unstressed triggers at causing VV coarticulation in Spanish.

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

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Table 6. Post hoc results of stress by target by trigger interaction for all models

Target vowel	Stress	Significance and difference in means			
		anticipatory edge	anticipatory midpoint	carryover edge	carryover midpoint
Target /e/	Target stressed	0.044*	ns	0.056**	ns
	Trigger stressed	0.043*	ns	0.088***	0.054***
	Neither stressed	ns	ns	0.08***	0.049**
Target /o/	Target stressed	ns	ns	0.047*	ns
	Trigger stressed	0.034*	ns	0.079***	0.035*
	Neither stressed	ns	ns	0.047*	ns

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$; ns, not significant.

trigger coarticulation with greater frequency. Thus, unstressed segments, which involve less exaggerated gestures, are less effective at triggering coarticulation.

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).

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 (Table 6) 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), 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 Hz for /e/, but only 99 Hz for /o/. Our 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, 2013). The current data suggest that, within a single vowel inventory, greater acoustic variability may be predictive of increased susceptibility to coarticulation.

5 Conclusions

The results of the present study demonstrate that VV coarticulation in Spanish is governed by a complex interaction between several factors, including the level of stress present on the target and trigger vowels, the identity of each vowel, and the direction of coarticulation. The data show that, as expected, stressed vowels were less susceptible to VV coarticulation than unstressed ones. We also observed that stressed vowels are better triggers of coarticulation than unstressed ones. We were therefore able to clarify that both tendencies, frequently conflated in previous disyllabic designs (where less coarticulation on stressed targets could also be explained by weaker effects from unstressed triggers), are independently valid. Thus, the hierarchy of coarticulation frequency and magnitude as a function of stress that emerged in the present study is the following: stressed triggers + unstressed targets > unstressed triggers + unstressed targets > unstressed triggers + stressed targets. At the same time, we 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 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.

These results elucidate the complex and interconnected nature of speech production, where multiple factors contribute simultaneously to the acoustic make-up of individual speech sounds. Furthermore, the results remind us that in designing investigations of multifaceted phenomena such as coarticulation, careful attention needs to be paid to prosodic and contextual conditions, direction of propagation, and the nature of the target units, as each of these may alter the magnitude of the influence wielded by other factors.

5.1 Future Research

One of the primary contributions of the current study is its ability to consider the effects and interactions of multiple factors on VV coarticulation simultaneously, exploring the ways in which one factor can inhibit coarticulation in particular contexts and obscure the impact of other factors when considered in the aggregate. Future research should expand this exploration of interactions among factors inhibiting or encouraging coarticulation as well as exploring a number of issues not addressed here. Key among these are the relative influences of the first and second languages on VV coarticulation, the applicability of the current findings across other dimensions (most prominently, height), and the role of individual differences. Zellou (2017) found that some aspects of perception related to coarticulation were subject to a production-perception link, wherein individuals who regularly produced stronger nasal coarticulation were also more proficient at discriminating nasal coarticulation (though not at rating its strength). However, it is not yet known whether individual differences play a similar role in VV coarticulation.

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Statement of Ethics

Subjects provided written informed consent, and this research was overseen by the Purdue Institutional Review Board under Protocol No. 1610018272.

Disclosure Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Jenna Conklin had a primary role in experimental design, data collection, data annotation and analysis, and manuscript preparation.

Olga Dmitrieva made substantial contributions throughout the project, including in experimental design, data analysis, and manuscript preparation.

Appendix A

Target Words

kekéke	kokóke	pepópo
kekeké	kokoké	pepopó
kékeke	kókoke	pépopo
kekéko	kokóko	popépe
kekekó	kokokó	popepé
kékeko	kókoko	pópepe
kekóko	pepépe	popópe
kekokó	pepepé	popopé
kékoko	pépepe	pópope
kokéke	pepépo	popópo
kokeké	pepepó	popopó
kókeke	pépepo	pópopo

Appendix B

Carrier Phrases

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.[1] 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 Marcoss 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.

[1] 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.

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