


Contextual frequency effects in children's phonetic variation: The case of Spanish word-initial /d/

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Abstract

Language variation is demonstrably affected by accumulated experiences reflecting the consequences of the contexts in which words are most frequently used. Yet, these contextual frequency effects are seldom explored in children's speech. This study uses a corpus-based approach to investigate how 29 Spanish-speaking children, aged 5–15, realize word-initial Spanish /d/ as a function of accumulated experiences with /d/-initial words in articulatory contexts that promote reduction. Contextual frequency effects are also examined in 12 Spanish-speaking adults from the children's community. Cumulative experience is estimated as the form's frequency of occurrence in a specific context that promotes a specific variant. Results reveal contextual frequency effects in both the child and adult data. Moreover, the extent of the contextual frequency effect is comparable across generations.

Keywords: exemplar models; contextual frequency effects; phonetic variation; child language acquisition

Introduction

Every time a word is used, the immediate phonetic context impacts the phonetic form of said word. This is reflected in the phonetic variation of specific sounds, such as in American English word-final -t/d deletion. More specifically, word-final -t/d deletion is more common before consonant-initial words than before vowel-initial words (Bybee, 2002; Raymond, Brown, & Healy, 2016). In addition to such online contextual effects, language users' accumulation of experience with the repercussions of the context in which the word is used influences phonetic variation. Important to the current study, when a word occurs more frequently in a phonetic environment that favors one variant over another, that word is more likely to be produced using the favored variant in other phonetic environments where the variant may not be favored. American English -t/d deletion also provides an example of the consequence of a word's frequent

occurrence in a specific phonetic environment: the likelihood of deletion increases the more often t/d-final words precede consonant-initial words even when those words precede vowel-initial words (Raymond et al., 2016). More specifically, in contemporary spoken American English, the word *lift* precedes consonant-initial words in 60% of occurrences whereas *craft* only occurs in this environment 38% of the time; consequentially, when these words precede vowel-initial words, the likelihood of deletion is much higher in *lift* than in *craft* (Raymond et al., 2016:201). This contextual frequency effect arises from language users' systematic storage of episodic memories (i.e., exemplars) which retain fine-grained phonetic detail resulting from the context in which the word was used, among other sources of variation (Bybee, 2001:50–54, 2002, 2010:19). Furthermore, as speakers accrue highly detailed exemplars of a word in a particular context, subsequent productions increasingly reflect the phonetic repercussions of the context in which the word is most frequently used (E.L. Brown, 2018; Bybee, 2002). While there is ample evidence of contextual frequency effects in adults' phonetic variation (e.g., Brown, 2023; Brown, 2015; Bybee, 2002; Lease, 2023; Raymond et al., 2016, among others), it is undetermined if contextual frequency also impacts children's phonetic variation.

Nevertheless, there is reason to expect contextual frequency effects in children's phonetic variation. Previous research in children's spontaneous speech has found that children's phonetic forms of words are impacted by immediate contexts from a very young age (Miller, 2013; Smith, Durham, & Fortune, 2009), which indicates that children start accumulating contextualized memories early on. Other research indicates that from infancy language users track probabilistic co-occurrences of linguistic units and form expectations about the contexts in which the units are used (Hay, Pelucchi, Estes, & Saffran, 2011; Lew-Williams & Saffran, 2012). In addition, cases of word-specific phonetic variation in children's naturalistic language data suggest that children store the fine-grained phonetic information associated with the probabilistic occurrence of phonetic forms in individual lexical items from usage events in long-term memory (Miller, 2013; Smith & Durham, 2019). Furthermore, in experimental tasks, young children's non-target-like productions reflect the context in which words often occur. For instance, 2-year-old French-speaking children's productions of *zarbe* rather than *arbe* "tree" arise from the frequent use of the plural form of the vowel-initial noun and the preceding determiner *les* "the.PL" (i.e., *les arbes* "the trees") (Chevrot, Dugua, & Fayol, 2009). In sum, both experimental tasks and corpus analyses show that immediate contexts affect children's phonetic variation and that young children have the capacity to track and store probabilistic distributions of a word's variable forms. Additionally, contextual frequency effects have been found to influence children's morphosyntactic variation (Brown & Shin, 2022). Together, this suggests we can expect contextual frequency effects in children's phonetic variation.

To investigate if accumulated experience with words' usage in contexts that condition specific phonetic forms arise in children's phonetic variation, the present study adopts a contextual frequency measure called *Form's Ratio of Conditioning* (FRC), which has been used to examine adults' phonetic variation (E.L. Brown, 2015, 2018; Bybee, 2002; Forrest, 2017) and children's morphosyntactic variation (Brown & Shin, 2022). More specifically, the present study uses a corpus-based approach to investigate word-initial /d/ variation among Spanish-speaking children, ages 5 to 15 years,

and Spanish-speaking adults from the same community. In both generations, /d/ realizations are highly variable: ranging from stops to complete deletions. Adults' Spanish /d/ variation has received attention in both laboratory and variationist analyses (e.g., Colantoni & Marinescu, 2010; Gradoville, Waltermire, & Long, 2021; Torres Cacoullos & Berry, 2018). Importantly, previous research already indicates that contextual frequency impacts both bilingual and monolingual Spanish-speaking word-initial /d/ variation (E.L. Brown, 2015, 2018). The current study aims to examine whether children's /d/ variation is also impacted by their accumulated experiences with /d/-initial words in articulatory contexts that promote reduction. Additionally, it investigates the factors that can mediate the strength of the contextual frequency effect in both the children and adults, as has been found for several lenition variables in adult language data but has not been explored for /d/ variation (e.g., Brown, 2020; Forrest, 2017; Raymond & Brown, 2012). Overall, the study contributes to our understanding of how language users' cumulative experiences with the contexts in which words occur impact phonetic variation.

The consequences of contextual frequency on phonetic variation

Contextual frequency effects form part of the theoretical framework of exemplar models of lexical representation (Bybee, 2001, 2010). Here, one fundamental assumption is that usage and domain-general cognitive processes systematically shape all levels of linguistic structure, in both production (Pierrehumbert, 2001, 2002) and perception (Todd, Pierrehumbert, & Hay, 2019). An exemplar model of lexical representation posits that each experienced word creates an exemplar that can be stored in long-term memory within an associative network of lexical representations.

Exemplars' phonetic forms are highly detailed and embedded with information about the articulatory context in which it was used. Consider the /d/-initial Spanish word *dijo* '(3SG) said.' The preceding context consistently and strongly influences the amount of constriction in /d/: realizations are less constricted when preceded by vowels relative to when the segment is produced after nasals, /l/, or is utterance-initial (Eddington, 2011; Simonet, Hualde, & Nadeu, 2012). Thus, the /d/ realization of *dijo* is [d]-like given a preceding nasal, /l/, or pause, whereas it is [ɔ̞]-like when preceded by a vowel. New exemplars are mapped to lexical representations according to their typicality and dissimilarity to previously experienced exemplars (Todd et al., 2019). This systematized and detailed storage system is made possible by domain-general processes of categorization and rich memory storage (Bybee, 2010:6).

Individual words' unique distributions of phonetic variants arise from this accumulation of redundant and fine-grained information in lexical representations. For instance, since the word *dijo* most frequently follows a vowel, most accumulated exemplars in the lexical representation will begin with [ɔ̞]-like sounds. As a result of accumulating these forms in memory, this redundant and subphonemic information impacts subsequent production: new forms *dijo* are more likely to be produced with a [ɔ̞]-like sound even when they are not in a [ɔ̞]-favoring environment given an abundance of approximant variants in the lexical representation. The word's unique range of phonetic variation reflects the FRC, which is the form's frequency of occurrence in a specific context that promotes a specific variant (E.L. Brown, 2018; Bybee, 2002). As

lexical representations continually accrue exemplars with the same phonetic form, the next selected phonetic form of the word is likely to be one that reflects the context in which the word most frequently occurs, because many of the stored exemplars contain a phonetic form that reflect the word's most frequent context. This outcome is referred to as an FRC effect (E.L. Brown, 2015, 2018; Bybee, 2002; Raymond et al., 2016), which is the specific type of contextual frequency effect examined here.

Variation in Spanish-speaking adults' word-initial /d/ realizations exhibits an FRC effect. More specifically, Brown (2015) examined /d/ realizations as a function of their frequency of use in contexts that promoted /d/ reduction in Spanish–English bilingual adults. The FRC variable was calculated as the number of times a /d/-initial word occurred in a reducing context out of a word's total number of occurrences. Words were grouped as “High FRC” (FRC > 50) or “Low FRC” (FRC < 50). The analyses revealed a significant effect of the FRC variable; /d/ reduction was significantly more likely in the high FRC words, where 71.5% of tokens were reduced (i.e., produced as [ð̥] or [ø] rather than [d]), than in the low FRC words, where only 37% of tokens were reduced. More specifically, the likelihood of a reduced variant in a non-reducing context (which favors [d]) was higher in a word like *dan* “(3PL) give,” which frequently occurred in reducing contexts, rather than in a word like *dinero* “money,” which infrequently occurred in reducing contexts. Put differently, an accumulation of reduced /d/ forms in lexical representation, given *dan*'s frequency of use in reducing contexts, overcame what was promoted by the immediate context. An experimental study conducted with 18 adult Spanish-speakers who read /d/-initial words in isolation revealed the same result (E.L. Brown, 2018). Another important finding from these two studies is that while contextual frequency significantly affected /d/ variation, lexical frequency did not.

While these studies demonstrate that FRC effects bias production, over and above what is promoted by immediate phonetic environments, other studies additionally find that FRC effects are mediated by the contexts in which words occur. For example, in studies of spectral and temporal reduction of Spanish word-final /s/, reduction was significantly more likely as /s/-final words increased in their frequency of use in a reducing context; however, the effect was only evident when words were produced in the reducing contexts (E.K. Brown, 2018). Relatedly, an FRC effect on Spanish word-final /s/ voicing was “magnified” in the conditioning context such that the relationship between the voiced variant and FRC was stronger in the conditioning context and weaker, but existent, in other contexts (Brown, 2020:13). Contextually-dependent FRC effects were also found for -t/d deletion in American English (Raymond et al., 2016). The findings of these studies indicate that the contexts in which words occur consistently exert a strong influence on production, and that this alters the strength of FRC effects.

Some studies additionally demonstrate that FRC effects can be mediated by words' frequency of use. For example, another study on Spanish word-initial /s/ reduction found that the FRC effect only applied to higher frequency words, and there was no relationship between FRC and /s/ reduction in the lower frequency words (Raymond & Brown, 2012). Relatedly, a study on American-English speakers' alternation between [ŋ] and [n] for words ending in unstressed *-ing* demonstrated that as lexical frequency and the frequency with which an *-ing* word was in a [n]-favoring context increased, [n] was significantly favored, yet the FRC effect was assuaged at lower frequencies

(Forrest, 2017). Together, the findings from these studies suggest that the repercussions of repeated usage for lenition variables are stronger in higher frequency words, with minimal to no influence for lower frequency words. Previous research on FRC effects in Spanish /d/ variation has not considered how the segmental context and lexical frequency could mediate the FRC effect. To address this small gap in the literature, the current study will analyze adult Spanish-speakers' /d/ variation as a function of these interactions.

While this body of literature demonstrates that adult language variation is demonstrably affected by accumulated experiences reflecting the consequences of the contexts in which words are most frequently used, such FRC effects are seldom explored in children's speech. To my knowledge, the study by Brown and Shin (2022) represented the first and only investigation of FRC effects in children's language. The study investigated if and when FRC effects were evident in children's morphosyntactic variation. They examined the acquisition of the factors that influence Spanish subject pronoun expression in two age cohorts of monolingual Spanish-speaking children. The FRC measure was operationalized as the number of times a verb form occurred in a non-coreferential context, favoring subject pronoun expression, out of all its occurrences (up to 100 tokens). The results demonstrated that the younger children's (ages 6–7) and the older children's (ages 8–9) subject pronoun expression was influenced by switches in subject reference; all children were significantly more likely to produce subject pronouns when there had been a switch in reference than when reference was maintained. Additionally, the older children's subject pronoun usage was impacted by the frequency with which verbs were used in switch-reference contexts: they were more likely to produce subject pronouns with verbs that frequently occurred in switch-reference contexts and this effect held even when the verb was used in a context where reference was maintained, where subject pronouns are disfavored. The authors posit that children's sensitivity to online contexts is a precursor to the emergence of these effects and that the FRC effect only emerges from the continued accumulation of experience with these probabilistic distributions.

The present study continues to examine FRC effects in child language data. While the FRC effect impacted children's subject pronoun expression (Brown & Shin, 2022), it is undetermined if FRC effects influence other aspects of children's speech. Here, FRC effects are explored in Spanish-speaking children's word-initial /d/ variation. This variable was selected since FRC effects on Spanish word-initial /d/ are already found in bilingual and monolingual adult language data (E.L. Brown, 2015, 2018), the children's realizations are variable, and in comparison to other Spanish voiced stops, /d/ shows a higher rate of lenition in general (Colantoni & Marinescu, 2010; Eddington, 2011). Furthermore, it is undetermined if FRC effects can arise earlier in the acquisition process: Brown and Shin (2022) found an FRC effect among the 8- and 9-year-olds but not the 6- and 7-year-olds. Relatedly, Brown and Shin (2022) did not test the possibility that FRC effects in child language data are impacted by factors such as the discourse context. Nevertheless, results from adult language data indicate that FRC effects are mediated by factors such as the context in which words occur and by lexical frequency (e.g., E.K. Brown, 2018; Forrest, 2017). If these variables mediate the strength of FRC effects among adult speakers, they may also similarly influence FRC effects during childhood. The specific research questions and predictions are:

- RQ1: Does an FRC impact Spanish-speaking children's and adults' realizations of word-initial Spanish /d/?
- P1: FRC impacts realizations of word-initial Spanish /d/, such that /d/ is less occluded as words increase in their frequency of use in reducing contexts.
- RQ2: At what age is the FRC effect apparent?
- P2: The FRC effect is apparent only after children's realizations of word-initial /d/ exhibit a sensitivity to the preceding context, which serves as the basis for the FRC effect.
- RQ3: Do the segmental context and lexical frequency mediate the FRC effect?
- P3: Given the results for other lenition variables (e.g., E.K. Brown, 2018; Forrest, 2017), the FRC effect may be stronger in higher frequency words and in phonetic environments that do not favor occluded variants.

Methodology

Selected corpus and speakers

The data come from *Shin's Corpus of Spanish in Washington and Montana* (Shin & Van Buren, 2016). This corpus contains sociolinguistic interviews with families of Mexican descent that migrate to Montana each summer for agricultural work and reside in Washington the rest of the year. From the 32 children included in the corpus, the data for 29 children aged 5–15 were selected. Children under age 5 were excluded since they did not produce enough tokens of word-initial /d/ and, at times, produced substitutions for /d/. The present study only focuses on realizations of word-initial /d/ that are found among adults (i.e., [d], [ð], and [ø]) (Hualde, 2013:129-142). All included children produced these allophones, and they did not produce any substitutions for /d/.

The children selected for the present study all speak Spanish, and they are bilingual in Spanish and English to varying degrees. The children were also born either in the U.S. (in California or Washington) or in Mexico. Measures of language use as obtained from background surveys are not available. While measures of English and Spanish language use are unaccounted for in the present study, the children live in a tight-knit community of Spanish speakers, and their Spanish linguistic patterns have not previously indicated influence from English (Lease, Shin, & Bird-Brown, 2022; Shin & Van Buren, 2016). Additionally, preliminary visualizations of the U.S.- and Mexico-born children's data do not reveal any glaring differences in usage patterns (see Figures A1 and A2 in the online appendix).

The data for 12 adults (6 women, 6 men) in the children's community were also included to provide a comparison group for the children's results and to explore the relationship between FRC and the mediating variables on /d/ realizations in adult language data, which has not been done before. The adults' ages range from 20 to 71 (mean = 40.45, SD = 17.48). Eleven of 12 adults were born in Mexico, and 1 was born in the U.S. The age of arrival in the U.S. varied from arriving at age 40 to being born in the U.S. (mean = 20.75, SD = 14.10). Only three of the adults reported speaking English

at the time of their interview.¹ While the sample population is heterogenous in their English exposure and use, it is worth restating that FRC effects in Spanish word-initial /d/ have been identified in both Spanish–English bilingual and Spanish monolingual speakers (E.L. Brown, 2015, 2018).

Dependent variable: constriction in Spanish /d/

In Spanish, productions of /d/ range from realizations with a full closure to outright deletion (Eddington, 2011; Hualde, 2013:129–142; Simonet et al., 2012). This variability in the amount of constriction is often consolidated into two allophones—[d] and [ḑ]—although phonetic zero [ø] is also common (Hualde, 2013:129–142). Traditionally, Spanish /d/ is realized as [d] in post-nasal, post-/l/, and post-pause contexts, whereas the reduced allophones (i.e., [ḑ] and [ø]) are realized elsewhere, in post-vocalic and other post-consonantal contexts (Hualde, 2013:129). Large-scale studies in bilingual phonological development indicate that by age 4;0 Spanish–English bilingual articulate /d/ allophones in the expected phonetic environments with over 90% accuracy (Acevedo, 1993). Acoustic analyses with intensity-based measures of /d/ extracted from spontaneous speech provide some support for this allophonic distribution: realizations are significantly more constricted after pauses, nasals, and /l/ (Eddington, 2011). However, realizations are also significantly more constricted after fricatives, as compared to post-vocalic contexts (Eddington, 2011). Furthermore, the amount of constriction in /d/ realizations is not found to differ significantly following high vowels, nasals, and fricatives (Simonet et al., 2012). Finally, /d/ realizations are significantly less constricted after low and mid vowels, as compared to high vowels (Colantoni & Marinescu, 2010; Simonet et al., 2012). In sum, acoustic analyses reveal a continuum in the amount of constriction in /d/ throughout these contexts: at one extreme, /d/ is least constricted following non-high-vowels, and, at the other extreme, /d/ is most constricted utterance initially.

To identify tokens of word-initial /d/, the speech was orthographically transcribed in *Praat* (Boersma & Weenink, 2023), and boundaries were placed around sequences of words that were separated by less than 200 milliseconds (Calder, 2019). Then, the words, syllables, and segments were automatically segmented out with *FaseAlign* (Wilbanks, 2022). Afterward, the alignment and labeling were manually checked. As for alignment, the boundaries of the consonant intervals were aligned to include the intensity valley associated with the consonant and the intensity peak of the following vowel (Eddington, 2011). For weak realizations of /d/ where the spectral and waveform characteristics of the consonant were (nearly) identical to those of the surrounding context, the exact location of each sound was determined perceptually, following prior analyses of Spanish /d/ (Gradoville et al., 2021). As for labeling, the intervals of adjacent vocalic phones that formed a vocalic sequence were merged, monosyllabic function words coded as “stressed” were recoded as “unstressed,” and the lexical stress coding for each word was checked and corrected as necessary. The procedure also involved marking tokens that needed to be excluded due to background noise, among other reasons. After removing exclusions, the children’s dataset included 1069 tokens, and the adult dataset included 591 tokens.

In the present study, the amount of constriction in Spanish word-initial /d/ is modeled via a consonant–vowel intensity difference, or simply intensity difference. This measure is often used in analyses of /d/ variation in adult speech (Colantoni & Marinescu, 2010; Eddington, 2011; Gradoville et al., 2021; Simonet et al., 2012), and it has been applied to child speech (Fabiano-Smith et al., 2015). Intensity differences were calculated by subtracting the minimum intensity of the consonant from the maximum intensity of the following vowel. The children’s intensity differences range from 0 to 28.36 dB, with a mean intensity of 7.31 (5.48) dB. The adults’ intensity differences range from 0 to 26.72 dB, with a mean intensity difference of 5.21 (4.37) dB. These distributions are comparable to what is found for other adult and child Spanish speakers (Colantoni & Marinescu, 2010; Eddington, 2011; Fabiano-Smith et al., 2015; Simonet et al., 2012).

Estimating cumulative usage: FRC_{NHV}

The present study considers how accumulated experience with word-initial /d/ after non-high vowels affects the realization of /d/. This context was chosen because previous research suggests that /d/ is least constricted following non-high vowels (Colantoni & Marinescu, 2010; Simonet et al., 2012). In the present study, this variable is referred to as *Form’s Ratio of Conditioning following a non-high vowel*, FRC_{NHV} for short.

The FRC_{NHV} value for each /d/-initial word was derived from a reference corpus that combined five corpora of Spanish–English bilingual speech since FRCs calculated from bilingual data are a better predictor of bilinguals’ phonetic variation than FRCs calculated from monolingual data (Brown, 2015). The reference corpus has 1,290,022 words, and it contains the following corpora: *Corpus del Español del Sur de Arizona* (Carvalho, 2012), the *New Mexico Spanish–English Bilingual* corpus (Torres Cacoullous & Travis, 2018), *Shin’s Corpus of Spanish in Washington and Montana* (Shin & Van Buren, 2016), the *Corpus of Spanish in the Southwestern United States* (Lope Blanch, 1990), and 18 transcribed interviews from the *New Mexico and Colorado Spanish Survey* (Bills & Vigil, 2008).²

FRC_{NHV} values for each /d/-initial word were calculated as the proportion of tokens of a /d/-initial word occurring after a word ending in a non-high vowel (i.e., /a e o/) out of the total number of tokens of that /d/-initial word in the reference corpus. The proportion was then multiplied by 100. For example, the word *da* “(3SG) gives” most often occurred after a non-high vowel, and the FRC_{NHV} associated with this word is 81 (= 335/413). The higher the FRC_{NHV}, the more often the word occurs in a context that decreases the amount of constriction in /d/. Therefore, it is expected that the higher the FRC_{NHV}, the lower the intensity difference. This calculation follows previous methodologies examining FRC effects (e.g., Brown, 2023; E.L. Brown, 2018; Raymond et al., 2016). The online appendix contains R code that can be used to automatically calculate the FRC values from segmental contexts.

Words that occurred less than four times in the reference corpus were excluded, since results obtained for words with few tokens can be spurious (Brown, 2020). After these exclusions, 1,054 tokens and 113 word types remained in the analysis for the children, and 574 tokens and 126 word types remained for the adults. While others have removed words with FRCs of 0 or 100, indicating that the word occurs categorically in

one context (e.g., Lease, 2023), the results were the same with or without these words, so they remained in the dataset. The distribution of FRCs was comparable across the children's and adults' discourse. In both datasets, the FRCs range from 0 to 100, with an average FRC of 52 (SD = 27) in the children's data and an average FRC of 53 (SD = 23) in the adults' data. All FRCs were scaled around their respective mean for the analysis. In addition there is no correlation between FRCs and lexical frequency in either dataset (Children: [$r(111) = .05, p = .68$]; Adults: [$r(124) = .006, p = .52$]). Importantly, this demonstrates that the contextualized usage measure (FRC_{NHV}) and the decontextualized usage measure (lexical frequency) are independent measures of language use.

Statistical analysis

Mixed-effects linear regression models were used to investigate whether FRC_{NHV} affects the 5- to 15-year-old children's realizations of word-initial Spanish /d/, and, if so, the age at which the FRC effect is apparent and how the segmental context and lexical frequency mediate the FRC effect. One model was created for all children's data. The maximal model included three-way interactions for age * FRC * lexical frequency and age * FRC * preceding context to assess if the mediating factors captured variation in children of all ages. Factors known to impact Spanish /d/ realizations among adults and consonant weakening in general were also included (Bybee, 2001:112, 149; Colantoni & Marinescu, 2010; Eddington, 2011; File-Muriel & Brown, 2011; Simonet et al., 2012). These variables are as follows: **preceding context** (nasal, /l/, pause; other V/C (/i u s r/)); **non-high vowel** (/e a o/); **following context** (front vowel (/i e/)); **not-front vowel** (/a o u/); **stress** (stressed (*dice* /'di.se/ "(3SG) says"); **unstressed** (*después* /des.'pues/ "after")); and **speech rate** (# of syllables/second over the duration of the entire utterance with the /d/ token, excluding the syllables and duration of /d/-initial word). The speech rate values were severely positively skewed and, concordantly, the distribution of speech rate values was significantly different from the normal distribution [$W = .82, p < .001$]. There was also a non-linear relationship between the raw speech rate values and intensity differences, which violates the linearity assumption of linear regression (Levshina, 2015). As such, speech rate was log-transformed for the statistical analysis. The first level listed for categorical variables serves as the reference level in the statistical analyses. Intensity differences in each reference level are expected to be highest for that variable. Thus, with the categorical variables structured in this way, we focus on what factors promote /d/ reduction. Additionally, variables for if the **word was de** "from" or not and for if the **word was después** "after" or not were also included. The word *de* is extremely frequent and much more frequent than all other words in the dataset; its presence in the data may skew results related to lexical frequency. The word *después* is most often produced in a chunk of *y después* "and after" with very little constriction. The models also included a random intercept for speaker and a by-word random slope for age.

There is a possibility that the results of the maximal model reflect the linguistic behavior of the younger children rather than the whole group of sampled children since there is a much larger representation of younger children in the data: older children contribute fewer datapoints than younger ones and there are fewer older children

overall. In other words, this imbalance may obscure developmental patterns related to FRC effects. To address this possibility the children's dataset was divided into age cohorts based on the results of a conditional inference tree and a subsequent analysis of variance (ANOVA) demonstrating that children 8 years and younger ($n = 15$) have more constricted realizations than children 9 years and older ($n = 14$) [$F_{1,1052} = 33.86$, $p < .001$]. The split coincides with prior research on developmental changes in segmental articulations that finds that the magnitude and variability of segmental productions significantly differ between children ages 5–8 years and older children, with older children producing articulations with significantly lower magnitude and variability than 5- to 8-years-olds (Lee, Potamianos, & Narayanan, 1999). In other words, the cohorts are motivated by milestones in articulatory development as corroborated in previous research.

These age cohorts were used when illustrating the results of the maximal model with the raw data to give the reader the clearest picture of the FRC effect. Within each age cohort, a mixed-effects linear regression model was also used to test the interactions between FRC and the segmental context and FRC and lexical frequency to examine how widespread these interactions are in the sampled ages. The maximal models for each dataset included interactions between FRC and the preceding context and FRC and lexical frequency, the linguistic factors described above, and random intercepts for speaker and word. The resulting models for each age cohort are presented in the online appendix (Tables A1 and A2).

A mixed-effects linear regression was also used to analyze the adult data. The model included two-way interactions for FRC * segmental context and FRC * lexical frequency, the linguistic factors described above, and random intercepts for speaker and word.

Best-fit models were defined by removing fixed terms one-by-one starting with the term that would produce the lowest Akaike Information Criterion (AIC) value, if removed, until an optimal AIC value was obtained. Once the fixed terms were defined, the *step()* function was used to determine if the random intercepts and slopes were necessary.

Results

Children

Figure 1 plots the children's word-initial /d/ intensity differences by preceding context. The plot also contains the results of an ANOVA that indicates that the children's /d/ realizations are significantly less constricted when /d/-initial words are produced after non-high vowels in comparison to both the nasal, /l/, and pause contexts and other V/C contexts [$F_{2, 1051} = 79.77$, $p < .001$]. Importantly, this result suggests that their /d/ realizations are influenced by the conditioning context (i.e., preceding non-high vowels) on which the FRC variable is based. Figure 2 plots the children's word-initial /d/ intensity differences by FRC; /d/ realizations become less constricted as FRC increases. Indeed, there is a significant negative correlation between these two variables [$r(1052) = -0.15$, $p < .001$]. The mixed-effects linear regression was used to examine whether this FRC effect is mediated by the segmental context in which the word was produced and/or by lexical frequency, and the trajectory of this effect.

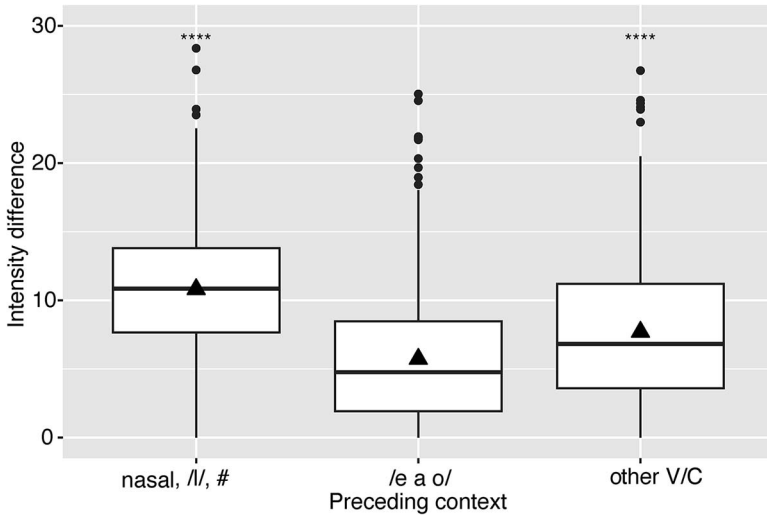


Figure 1. Intensity differences by preceding context.

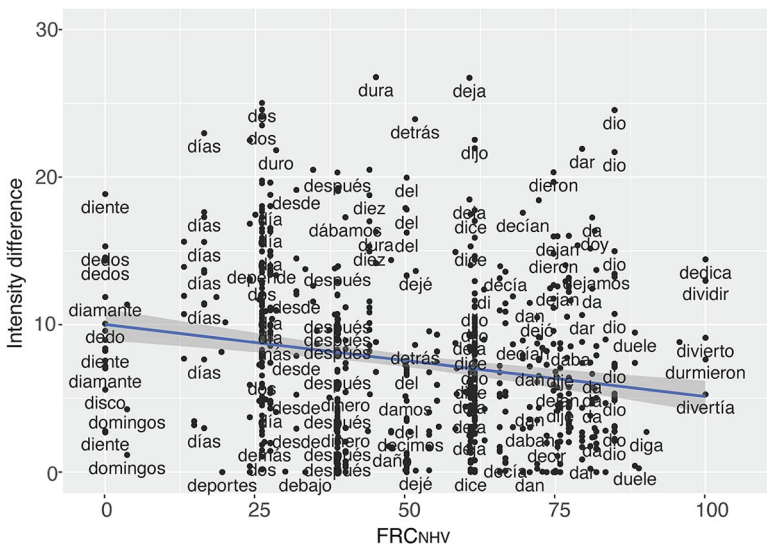


Figure 2. Intensity differences by FRC; excluding *de*.

The best-fit model indicates that intensity differences are significantly lower in preceding non-high vowel contexts and in the other V/C contexts, as compared to preceding non-high vowel contexts and in the other V/C contexts, as compared to preceding non-high vowel contexts and in the other V/C contexts (Table 1). The difference in intensity differences is larger between the non-high vowel and nasal, /l/, and pause contexts, as compared to the difference between the other V/C and reference contexts. Importantly, this result reiterates that the children’s /d/ realizations are influenced by

Table 1. Mixed-effects linear regression predicting intensity differences in children's word-initial /d/

	β	SE	t-value	p-value	n observations	Mean ID
Intercept (nasal, lateral, pause; stressed; not <i>después</i>)	26.75	2.84	9.40	<.001		
Log(Age)	-5.17	1.18	-4.40	<.001		
Preceding non- high vowel	-4.89	0.41	-11.93	<.001	555	5.73
Preceding other V/C	-2.61	0.46	-5.67	<.001	275	7.69
Log(Speech rate)	-1.35	0.54	-2.49	.01		
Lexical stress	-1.54	0.57	-2.70	.008	625	6.58
Log(Lexical frequency)	-0.26	0.14	-1.71	.09		
Scale(FRC)	4.19	1.35	3.11	.002		
Word is <i>después</i>	-3.68	1.65	-2.22	.04	80	4.89
Preceding non-high vowel:Scale(FRC)	-3.21	1.16	-2.76	.005	555	5.73
Preceding other V/C:Scale(FRC)	-2.10	1.20	-1.75	.08	275	7.69
Log(Lexical fre- quency):Scale(FRC)	-0.59	0.25	-2.34	.02		

Random intercepts: Word: $\sigma^2 = 2.11$; Speaker: $\sigma^2 = 1.95$; Residual: $\sigma^2 = 20.37$.
 Model fit: AIC = 6259.69; BIC = 6334.09; conditional $R^2 = .37$.

the conditioning context on which the FRC variable is based, and that this conditioning context promotes the most reduced /d/ realizations. The other linguistic factors that impact /d/ constriction are lexical stress and speech rate; intensity differences are significantly lower in unstressed syllables and with an increased speech rate. Additionally, intensity differences are significantly lower if the word is *después*. Intensity differences also significantly decrease as age increases.

In addition to an online effect of the segmental context, the best-fit model also indicates that the preceding context mediates the FRC effect: intensity differences significantly decrease as FRC increases when /d/-initial words follow non-high vowels (Table 1). There is also a marginal effect of FRC in the other V/C context (Table 1). Figures 3 plots the predicted intensity differences by preceding context as extracted from the model presented in Table 1. In this heatmap, the DV is represented by the shading while the independent variables are on the x and y axes. The darkest shade corresponds to the highest predicted intensity differences, with the most constriction, while the lightest shade corresponds to the lowest predicted intensity differences, with the least constriction. The model shows that intensity differences decrease as FRC_{NHV} increases in the non-high vowel, and somewhat so in the other V/C contexts.

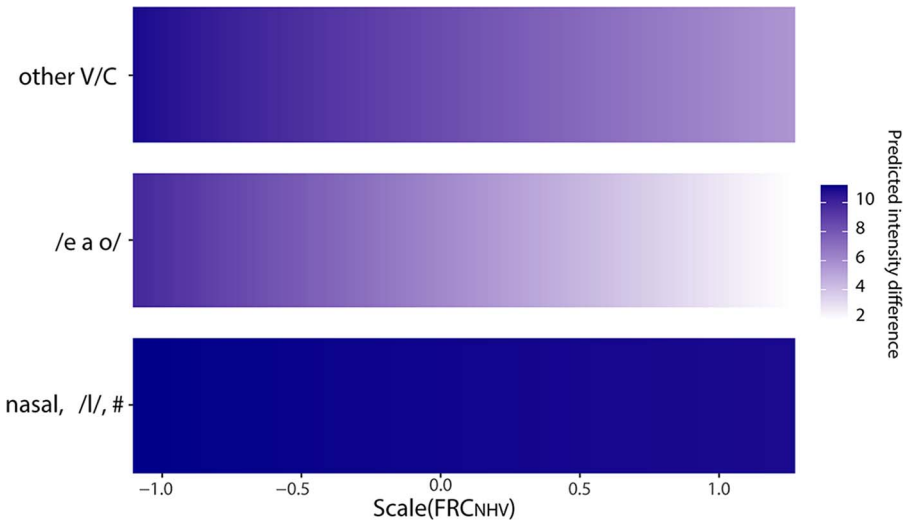


Figure 3. Predicted intensity differences by FRC_{NHV} and preceding context.

In Figure 3, this is evident in that the predicted intensity differences in the non-high vowel and other V/C panels shift from darker shades (at lower FRCs) to lighter shades (at higher FRCs). The best-fit model returns a significant effect of the term FRC; however, this value only reflects the predicted amount of constriction when a low-frequency word occurs after a nasal, /l/, or pause, where we already expect the most constriction. The shift in shading is less dramatic in the nasal, /l/, # panel and all shades are dark regardless of FRC.

Figure 4 illustrates this interaction in the raw data for each age cohort. In both groups, there is virtually no change in intensity differences as FRC increases in the nasal, /l/, # context (left panels). In contrast, there is a decrease in intensity differences as FRC increases in the other panels for both age-groups, although the slopes vary. The regression models for each age cohort indicated that there is a significant effect of FRC on intensity differences in the non-high vowel context, for both age cohorts, and in the other V/C contexts, for the 5- to 8-year-olds (see Tables A1 and A2 in the online appendix). These results show that the interaction between FRC and the preceding context, as found in Table 1, describes /d/ variation, to some extent, in both age cohorts.

Aside from this interaction, the best-fit model also indicates that intensity differences significantly decrease as words increase in lexical frequency and in FRC. The predicted intensity differences extracted from the model in Table 1 are plotted as a function of this interaction in Figure 5. Like Figure 3, the predicted intensity differences (DV) are represented by the shading whereas the two interacting independent variables are on the x and y axes. Additionally, the black points represent the predicted values. The visualization suggests that the FRC effect is stronger in higher frequency words. More specifically, for words with a log-transformed lexical frequency value greater than 4 (~55 occurrences in the reference corpus), intensity differences noticeably decrease

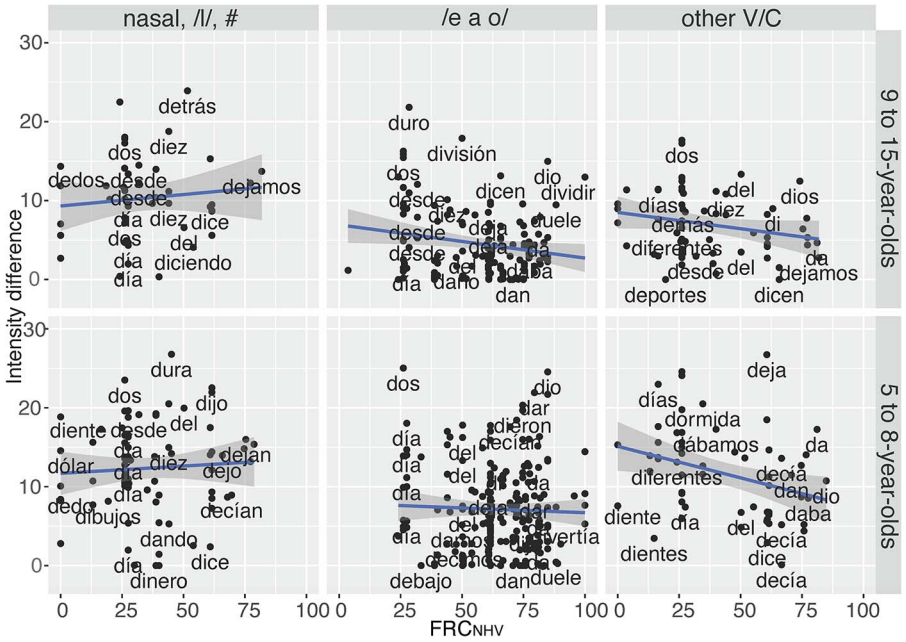


Figure 4. Intensity differences by FRC_{NHV} and preceding context for two age cohorts; excluding *de* and *después*.

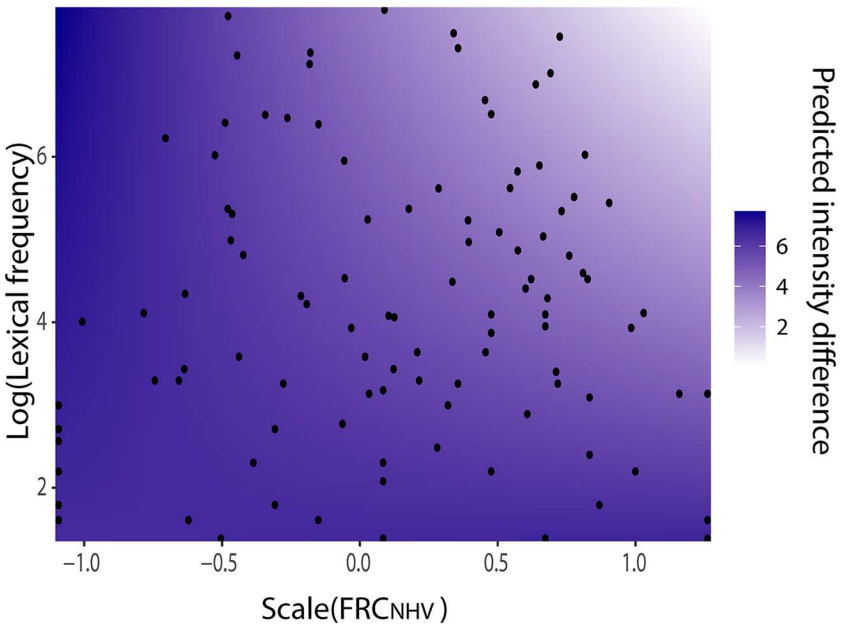


Figure 5. Intensity differences by FRC_{NHV} and lexical frequency; excluding *de*.

as FRC increases. In Figure 5, predicted intensity differences in these “high” frequency words shift from darker shades at lower FRCs to lighter shades at higher FRCs. In “lower” frequency words, there seems to be a weaker relationship between FRC and intensity differences; the associated predicted intensity differences are all dark shades, indicating greater constriction overall.

Figure 6 visualizes the interaction between FRC and lexical frequency in each age cohort. In both groups, there is a greater decrease in intensity differences as FRC increases in the higher frequency words (right panels) as compared to the lower frequency words (left panels). The regression models for each age cohort indicated that there is a significant interaction between FRC and lexical frequency in each group (see Tables A1 and A2). Importantly, the nature of the interaction is comparable across the age cohorts and models in the sense that increasing lexical frequency increases the potency of the FRC effect. Thus, as was the case for the interaction between FRC and the preceding context, this interaction between FRC and lexical frequency found in Table 1 describes /d/ variation in both age cohorts.

In sum, the results for the children reveal FRC effects on /d/ variation; the effect is stronger in higher frequency words and when /d/-initial words are in phonetic environments that already favor reduced variants. These findings mirror findings for adults’ phonetic variation with other lenition variables (e.g., Brown, 2020; Forrest, 2017). Furthermore, the FRC effect is evident in children ages 5- to 15-years-old, which

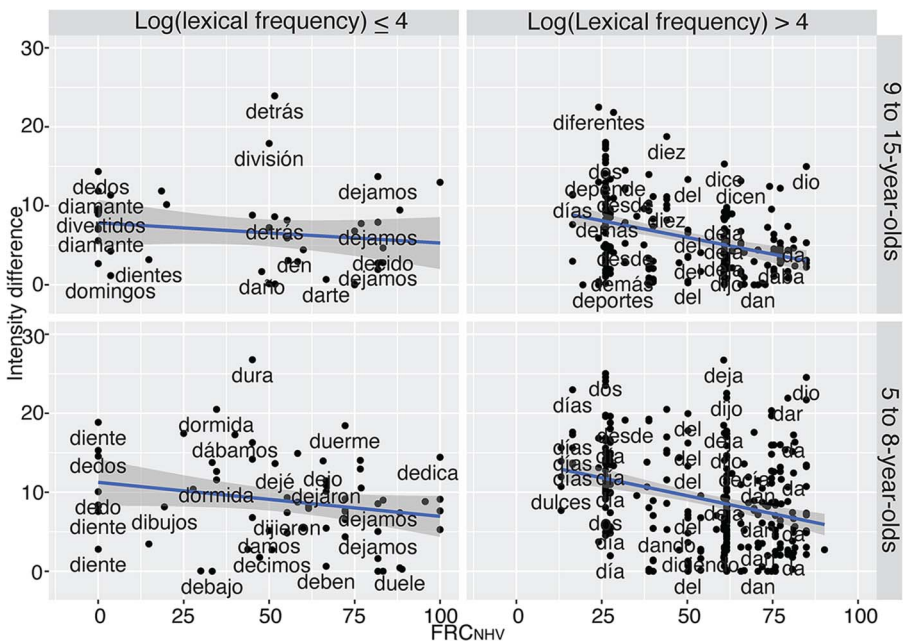


Figure 6. Intensity differences by FRC_{NHV} and lexical frequency for two age cohorts; excluding *de* and *después*.

contrasts research on FRC effects in children’s morphosyntactic variation (Brown & Shin, 2022).

Adults

The adults’ word-initial /d/ intensity differences are plotted by preceding context in Figure 7 and accompanied by the results of an ANOVA in which intensity differences were modeled as a function of the preceding context. This basic visualization and bivariate analysis demonstrate that the adults’ /d/ realizations are significantly less constricted when the /d/-initial words are produced after non-high vowels in comparison to both the nasal, /l/, and pause contexts and other V/C contexts [$F_{2,572} = 67.93$, $p < .001$]. Importantly, this result suggests that the adults’ /d/ realizations are influenced by the conditioning context on which the FRC variable is based. Whereas Figure 7 plots the “online” effect of the phonetic environment, Figure 8 plots the adults’ word-initial /d/ intensity differences by FRC. Here, it is evident that adults’ /d/ realizations become less constricted as FRC increases; there is a significant negative correlation between these two variables [$r(589) = -0.22$, $p < .001$]. The mixed-effects linear regression was used to examine if this FRC effect is mediated by the segmental context in which the word was produced and/or by lexical frequency.

The best-fit model for the adult data indicates that intensity differences are significantly lower in preceding non-high vowel contexts, as compared to intensity differences in the nasal, /l/, and pause contexts (Table 2). There is also a significant difference in intensity differences between the other V/C contexts and the nasal, /l/, and pause contexts. The difference in intensity differences is larger between the non-high vowel and nasal, /l/, and pause contexts, as compared to the difference between the other V/C and reference contexts. The best-fit model also demonstrates that intensity differences are significantly smaller in unstressed syllables as compared to stressed ones.

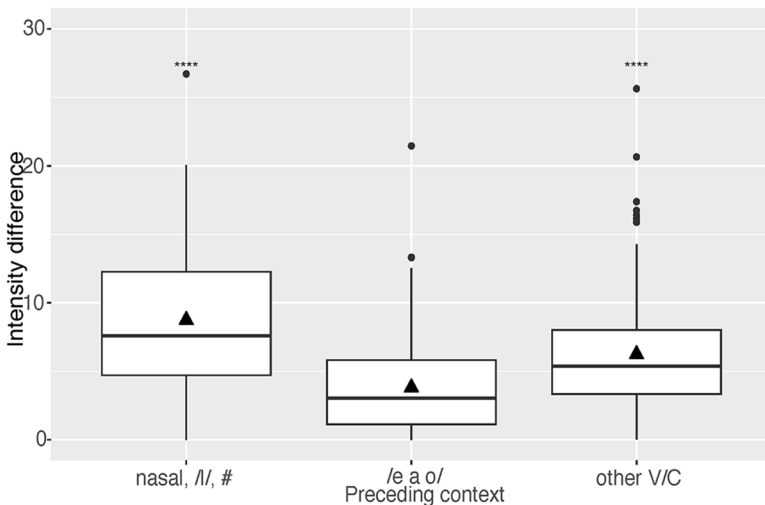


Figure 7. Intensity differences by preceding context.

(see Figure 9). While the best-fit model identified an interaction between the segmental context and FRC, the best-fit model did not retain the interaction between FRC and lexical frequency. Indeed, a visualization of the relationship between FRC and intensity differences for words with a log-transformed frequency greater than 4 and for words with lower frequencies demonstrates that intensity differences decrease at a similar rate in both “high” and “low” frequency words (see Figure 10). Words were binned this way to facilitate comparisons with the children’s results.

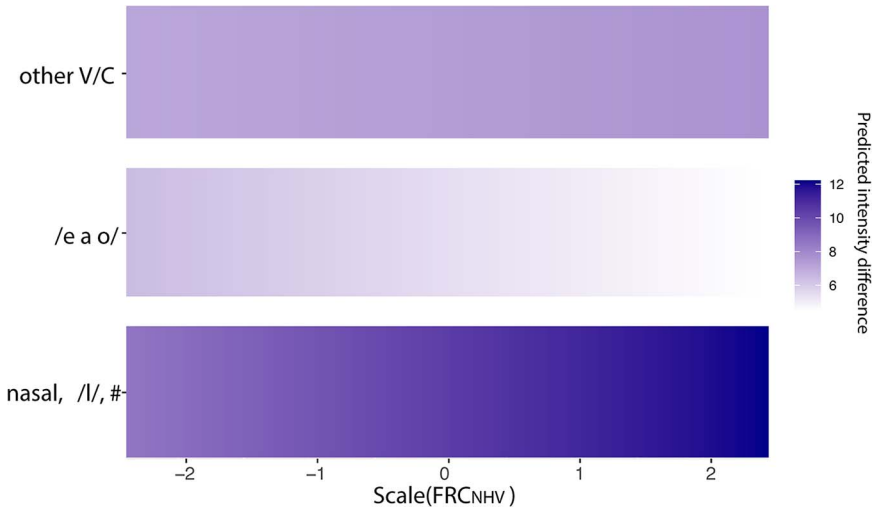


Figure 9. Predicted intensity differences by preceding context in adult data.

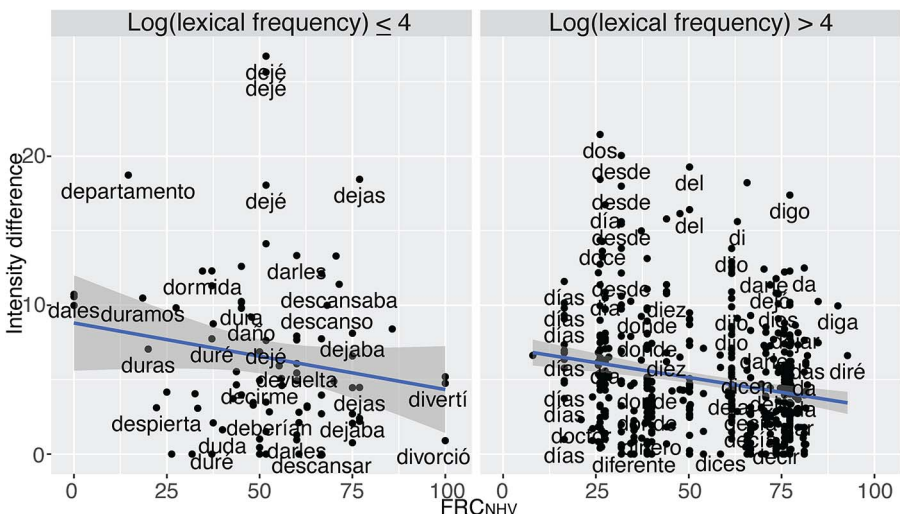


Figure 10. Intensity differences by FRC and lexical frequency in adult data; excluding *de*.

In summary, the results for the sample of adult data demonstrate that /d/ realizations are least constricted following non-high vowels, and that /d/ realizations become less constricted as the frequency with which words occur in this context increases. These results corroborate previous research on FRC effects in adult Spanish-speakers' word-initial /d/ (E.L. Brown, 2015, 2018). However, they also contribute new evidence that the FRC effect on /d/ variation is specific to certain segmental contexts, as has been found for other lenition variables (e.g., Brown, 2020; Forrest, 2017).

Discussion

The present study contributed a novel account of an FRC effect in child language data by examining whether 29 5- to 15-year-old Spanish-speaking children's and 12 Spanish-speaking adults' realizations of word-initial /d/ were influenced by the frequency with which /d/-initial words occur in an articulatory context that promotes segmental reduction in the initial /d/. To do so, the analyses adopted a novel and under-applied usage metric in studies of language variation and change and in child language acquisition research, called *Form's Ratio of Conditioning* (i.e., FRC_{NHV} in the present study) (E.L. Brown, 2018; Bybee, 2002). The variable estimated the amount of cumulative experience a language user has with individual /d/-initial words' usage in contexts that promote reduction.

Whereas previous research on child language data had only considered the FRC variable in interaction with age (i.e., Brown & Shin, 2022), the present study considered the joint effect of the FRC variable, the child's age, and both the preceding context and lexical frequency. Additionally, previous research on Spanish-speaking adults' /d/ variation had only considered the overall effect of FRC on realizations (E.L. Brown, 2015, 2018), yet other studies on lenition variables had found that the influence of the FRC effect is impacted by the segmental context and lexical frequency (e.g., Raymond & Brown, 2012; Raymond et al., 2016). In the current study, an analysis of adults' /d/ variation was also included as to provide an accurate comparison to the children's data, and in doing so filled this gap in the previous literature.

The results provide evidence that accumulated experience with /d/-initial words in reducing environments impacts both Spanish-speaking children and adults' /d/ variation. Additionally, they demonstrate that the segmental context and lexical frequency mediate the strength of the FRC effect in both the adults' and the children's data. In the children's data, the FRC effect was stronger in higher frequency words and in phonetic contexts where the repercussions of coarticulation did not contradict production of the phonetic forms predicted by words' frequent occurrence in reducing contexts. Dividing the children's data into age cohorts further demonstrated that these trends capture /d/ variation in children between the ages of 5 and 15 years. Like the children, the FRC effect in the adults' data was stronger in phonetic contexts that favored reduced variants, although lexical frequency did not mediate the strength of the effect.

The only other child language study to demonstrate the repercussions of cumulative usage using an FRC metric focused on morphosyntactic variation in Spanish-speaking children (Brown & Shin, 2022). Together these studies demonstrate that child language data also exhibit the well-established FRC effects found in adults'

speech. For instance, E.L. Brown (2015, 2018) found that the amount of constriction in the realizations of word-initial /d/ of Spanish-speaking adults was predictable from the frequency with which these words occurred in contexts that favor reduction. Likewise, the present study demonstrates that children's cumulative experience with the articulatory ramifications of reducing contexts also influence /d/-initial realizations.

The fact that these children's realizations of word-initial /d/ are affected by the FRC_{NHFV} variable supports the idea that language users' accrued experience with the articulatory consequences of the contexts in which words frequently occur skews the phonetic substance of lexical representations (Bybee, 2002; Pierrehumbert, 2001, 2002). The repercussion of this skewed distribution is that subsequent usage is biased toward producing (and perceiving) the word in the phonetic form most entrenched and active in lexical representation (E.K. Brown, 2018, 2023; E.L. Brown, 2018). More specifically, the children, like adults, experience the articulatory ramifications of the contexts in which /d/-initial words occur. The exemplars created from these experiences lexicalize the consequences of the articulatory context. Once mapped to lexical representations, each newly added exemplar incrementally adjusts and updates the distribution of phonetic forms. As lexical representations accrue numerous exemplars that come from iteratively using the word in the same type of context, distributions of phonetic forms become skewed toward the most frequently occurring forms. While the memories of these frequently experienced phonetic forms grow stronger, the memories of the phonetic forms that are infrequently experienced decay. As a result, children's subsequent usage is biased toward producing the phonetic form of the word in the context in which it most frequently occurs.

In addition to providing novel evidence for FRC effects in children's phonetic variation, the present study additionally demonstrates that the repercussions of accumulated experiences, evident in both the children's and adults' data, are mediated by the segmental context. More specifically, the amount of constriction in word-initial /d/ only significantly decreases as FRC_{NHFV} increases when words are in contexts that promote /d/ reduction. Put differently, even if reduced forms are lexicalized in the mental representation of these words, the extent of entrenchment is not great enough to override the articulatory outcome of contexts that do not promote these forms. Studies on adult Spanish-speakers' /s/ reduction (E.K. Brown, 2018, 2020) and adult American-English speakers' -t/d deletion (Raymond et al., 2016) also find that FRC effects are stronger in contexts that already favor the phonetic forms that are also promoted by the word's frequent occurrence in these environments. In these studies, it is also the case that phonetic environments that do not favor these variants mitigate the FRC effect.

It should be noted that, at no point in development or in the adults' data, is the FRC effect stronger than the main effect of the conditioning context. In other words, in each studied generation, the ramifications of the immediate contexts in which words occur strongly influence /d/ realizations, and it is this continued influx of articulatory experience that motivates and perpetuates the FRC effect. Like what has been demonstrated in computational models of exemplar dynamics (Pierrehumbert, 2001, 2002; Todd et al., 2019), the concomitant influence of the conditioning context and the FRC variable on /d/ realizations found in the present study exemplifies the relevance of

both the immediate speech context and the existing distribution of exemplars in lexical representation to explaining phonetic variation in speech production.

Aside from the mediating effect of the segmental context, the present study finds that increasing lexical frequency strengthens the repercussions of accumulated experiences in the children's data (Figures 5 and 6), which is found in studies on adults too (Forrest, 2017; Raymond & Brown, 2012). In these cases, the consistent addition of exemplars maintains the skewed distribution of phonetic content that is necessary for FRC effects (Pierrehumbert, 2001). Furthermore, increasing lexical frequency amplifies the level of exemplars' activation around a particular phonetic form and shrinks the distribution of retained exemplars over a phonetic space within a lexical representation (Pierrehumbert, 2001, 2002). This results in the even greater chance that the exemplars from the words' most frequent context dominate, and, importantly, for FRC effects to be stronger, or only evident, in higher frequency words. In the adults' data, however, there was no joint effect of lexical frequency and FRC. One possibility for this difference is that this interaction is sensitive to the words included in the analysis, although other hypotheses exist. Taking these results together with other research presenting cases in which lexical frequency has no effect on variation while FRC does (E.L. Brown, 2015, 2018), and in which *lower* lexical frequency strengthens the contextual frequency effect—in the case of paragoge (Lease, 2023)—highlight a need to further explore the relationship between frequency of use and contextual frequency effects.

While the results of the present study and those of Brown and Shin (2022) demonstrate that FRC effects impact children's linguistic variation, the trajectory of the FRC effect differs. Whereas Brown and Shin (2022) only found an FRC effect in the 8- and 9-year-old children, there was no interaction between FRC and age and the results were similar across age cohorts in the present study. This difference may be partially attributed to the developmental timelines documented for these variables: Spanish-speaking children develop a sensitivity to /d/'s allophonic distribution by age 4;0 (Acevedo, 1993), whereas children's sensitivity to switch-reference emerges by age 5;0 (Forsythe, Greeson, & Schmitt, 2021), at the earliest. Thus, it is possible that FRC effects on /d/ variation are *not* evident for children younger than age 5;0 if they are just starting to accrue experience with the articulatory consequences of the contexts in which /d/-initial words are used. Relatedly, FRC effects may emerge on different timelines given the differing frequencies with which children accumulate experience with the relevant words and conditioning contexts. Differing results may also be attributed to Brown and Shin (2022) only testing FRC in interaction with age, whereas the present study considered interactions between age and FRC, as well as their interaction with lexical frequency and the conditioning context. The results related to these interactions suggest that FRC effects in phonetic variation are evident from the age of 5 years, but that they are stronger to particular contexts and certain words. Future research can explore the possibility that FRC effects in children's morphosyntactic variation are evident in select contexts or words among young children.

Conclusion

Altogether, by investigating an FRC effect in Spanish-speaking children's word-initial /d/ realizations, the study fills a gap in the literature corresponding to the impact of

contextual frequency on children's phonetic variation. Importantly, the findings suggest that from a young age the repercussions of the contexts in which words occur are embedded and accumulate in lexical representation. The study adds to a growing body of literature on FRC effects which have continuously demonstrated that the consequences of the contexts in which words are used are absorbed into mental representations, rendering subsequent language use more reflective of this previous experience. This study demonstrates that contextual frequency impacts children's phonetic variation and that the extent of its impact in the case of Spanish word-initial /d/ is comparable to what is found in adults' phonetic variation and other lenition variables.

One outstanding and important question is, of course, how much experience is "enough" for contextual frequency effects to emerge in children's phonetic variation. The results of the present study suggest that by age 5 children already had "enough" experience. Investigating input patterns and younger children's variation could further elucidate how much experience is "enough" for the repercussions of cumulative usage to impact variation. A second outstanding question is whether the frequency with which words are used in particular contexts facilitates children's acquisition of variation. Some studies have reported that children first produce phonetic variation that is found in adults' speech in higher frequency words (Díaz-Campos, 2004). It may also be the case that patterns of phonetic variation first emerge in words that are often in the environments that favor particular variants. As demonstrated by the current study, answers to these questions can inform how usage-based approaches capture linguistic variation in speakers of all ages.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/S0954394524000176>.

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Competing interests. The author declares none.

Notes

1. Social factors also influence /d/ variation (Gradoville et al., 2021; Torres Cacoullous & Berry, 2018) so "age of arrival," "being monolingual versus bilingual," and "age" were also analyzed. The effects of these variables were not significant.
2. The transcripts of the 12 adults are used in this reference corpus. However, there are strong, positive, and significant correlations between the FRC values throughout the sub-corpora. Also, these transcripts only contribute .005% of the total words in the reference corpus. Therefore, any circularity attached to the results regarding the usage statistics is minimal.

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