Research Article

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Phonetic and phonological vowel reduction in Brazilian Portuguese

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Abstract: The present study examines the phonetic and phonological status of vowel reduction in Brazilian Portuguese. In order to compare the effects of duration and metrical structure, we tested the influence of duration on the realization of /a/ in five prosodic positions: word-initial pretonic, word-medial pretonic, tonic, word-medial posttonic, and word-final posttonic. The results revealed that, while effects of both phonetic duration and prosodic position had effects on F1 values for /a/, the categorical effect of prosodic position was much stronger and more reliable. In particular, F1 values for /a/ were best predicted by a two-way distinction between posttonic and non-posttonic syllable positions. Correlations between a vowel's duration and its F1 frequency were statistically significant but generally weak in all positions. We argue that these findings suggest that vowel reduction in Brazilian Portuguese primarily reflects phonological patterning rather than phonetic undershoot, although there was also evidence for some amount of undershoot. Brazilian Portuguese can therefore be said to have a mixed system of phonological and phonetic reduction. The present study discusses the results in the context of Brazilian Portuguese metrical organization, sound change, and the relation between phonetics and phonology.

Keywords: Brazilian Portuguese; phonetics-phonology interface; vowel reduction

1 Introduction

1.1 Phonological and phonetic vowel reduction

Crosslinguistically, unstressed syllables tend to exhibit shorter duration and lower amplitude compared to stressed syllables (e.g., Beckman 1986; Flemming 2004, 2006).

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Another prominent difference is the emergence of changes in vowel quality in unstressed syllables. These qualitative changes, often called vowel reduction, can be either categorical or gradient, depending on their phonological or phonetic status in a given language.

Phonological vowel reduction typically involves the neutralization of phonemic contrasts in unstressed positions (Barnes 2006, 2007; Crosswhite 2001; Flemming 2004, 2006; Fourakis 1991; Padgett 2004; Padgett and Tabain 2005). Such a phonological process therefore leads to smaller inventories of vowels in unstressed syllables relative to stressed syllables. Unstressed vowels in many languages neutralize to other vowels by lowering, raising, and/or centralizing. For instance, unstressed mid vowels /e, o/ in Belarusian merge with the low vowel /a/, and consequently, the inventory of the unstressed vowels reduces to [i, a, u] which is a sub-inventory of stressed vowels /i, e, a, o, u/ (Barnes 2006; Crosswhite 2001). Luiseño displays raising in the unstressed vowels. The unstressed mid vowels /e, o/ in Luiseño become high vowels [i] and [u] respectively, thereby reducing the inventory of /i, e, a, o, u/ in stressed syllables to [i, a, u] in unstressed syllables (Munro and Benson 1973). Catalan shows as centralizing well as raising in the unstressed syllables. Unstressed mid back vowels /o, ɔ/ in Catalan merge with /u/, and /e, ɛ, a/ are realized as /ə/. Consequently, the inventory of the unstressed vowels reduces to [i, u, ə] which is a sub-inventory of stressed vowels /i, e, ɛ, a, ɔ, o, u/ (Nadeu 2014, 2016).

In contrast, phonetic vowel reduction refers to articulatory undershoot of the vowel's target. In general, phonetic reduction is found to be greater in contexts of durational shortening,[1] when undershoot is expected to be more likely. Unlike phonological reduction, this process generates gradient rather than categorical change, resulting in a shrinkage of the phonetic space in which a given set of categories is realized (Barnes 2006, 2007; Fourakis 1991; Lindblom 1963; Mooshammer and Geng 2008; Nadeu 2014, 2016; Padgett and Tabain 2005). Previous studies have also shown that phonetic reduction can be gradiently conditioned by stress (Beňuš and Mády 2010; Fourakis 1991; Gay 1978; Nadeu 2014), speech rate (Barnes 2006; Fourakis 1991; Nadeu 2014), paralinguistic emphasis (Barnes 2007; Smiljanić and Bradlow 2005), and segmental context (Chen 1970; Lindblom 1963). An example of phonetic undershoot is shown in Figure 1, adapted from Flemming (2006).[2] This figure shows formant frequency values of five vowels in a [g_g] context differing in durations: 200, 125 and 100 ms. Figure 1 illustrates that the

1 Articulatory undershoot can also be affected by various factors such as speaking mode, clear versus conversational speech (Krause and Braida 2002).

2 The formant values were derived from Lindblom (1963)'s model, not measured formant frequencies.

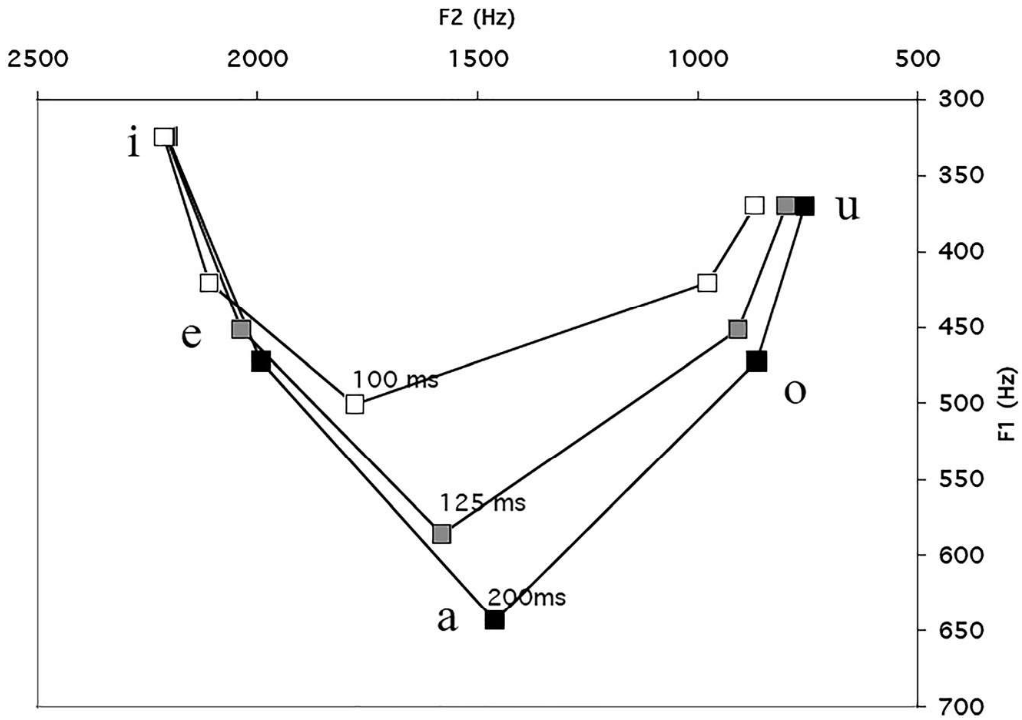

Figure 1: F1 & F2 of five vowels differing in durations: 100, 125 and 200 ms (adapted from Flemming 2006, based on Lindblom 1963).

vowels, especially the non-high vowels, exhibit more F1 target undershoot as duration decreases.

However, teasing apart phonetic and phonological reduction is often not straightforward in unstressed syllables, given that both phonological and phonetic reduction result in reduced duration and qualitative changes in vowels. Observing the effect of durational variation may be key to decoupling one from the other, especially increases in duration (Barnes 2002, 2006, 2007; Crosswhite 2001). Crosswhite (2001) argued that phonetic and phonological vowel reductions are similar in terms of the end result, but the causal relation is reversed. In phonetic reduction, reduced duration causes vowel target undershoot. That is, an articulator does not have enough time to reach its target, and so that articulatory is, in the end, undershot.

On the other hand, reduced duration is also an *effect* of phonological reduction. Given that higher vowels have inherently shorter duration than lower vowels, phonologically-driven vowel raising necessarily results in some amount of reduced duration. Consequently, the reversed causal relation leads us to different predictions about how changes in duration relate to changes in vowel quality; while we do not expect categorical changes in vowel quality (i.e., phonological reduction) to be triggered by changes in duration, we do expect gradient changes in vowel quality (phonetic reduction) to be – again, due to articulatory undershoot. In English, for example, durational change rarely affects categorical alternation between full vowels and schwa as in *tel*[ɛ]*graphy* and *tel*[ə]*graphic,* since the alternation depends categorically on an aspect of structure, namely metrical structure, i.e., stress. That is, even if a speaker produces *te**le**graphy* at a fast speech rate, the vowel is unlikely to be realized as a schwa, and even if *te**le**graphic* is produced slowly, the vowel is never expected to be realized as [ɛ].

A fundamental question in any study of vowel reduction is whether the particular case being investigated is phonetic or phonological in nature. A relatively small number of studies have asked this question about Russian, which is often understood as exhibiting two reduction patterns whose phonological status is rather uncertain (Barnes 2006, 2007; Padgett 2004; Padgett and Tabain 2005). First, the five-vowel inventory /i, e, a, o, u/ in stressed syllables is reduced to three vowels [i, u, a] in stress-adjacent pretonic syllables, as the underlying /i, e/ neutralize to /i/ and /o, a/ neutralize to /a/. In addition, in all other unstressed syllables, the neutralized /a/ undergoes a further reduction to [ə], producing the sub-inventory [i, u, ə]. The first pattern, referred to as "Degree 1 reduction," is described informally as "moderate" reduction, while the second one, "Degree 2," is more "severe" (see also Barnes 2006; Crosswhite 2001). Using hyperarticulated speech, Barnes (2007) found that /a/ and /o/ phonologically merge to /a/ regardless of the increased duration in stress-adjacent pretonic syllables (positions for Degree 1 reduction). However, in all other unstressed syllables (Degree 2 reduction), longer duration resulted in more [a]-like realizations (i.e., full vowels rather than [ə]). This suggests that Degree 1 reduction in Russian requires reference to a phonological process, while Degree 2, which can be accounted for by phonetic undershoot, does not.

1.2 Vowel reduction in Brazilian Portuguese

The aim of the present study is to expand the above discussion to Brazilian Portuguese, which is also reported to exhibit two different patterns of reduction in unstressed syllables. Like Contemporary Standard Russian, unstressed vowels in standard Brazilian Portuguese (henceforth BP) undergo qualitative changes that show two patterns (Barbosa 2012; Fails and Clegg 1992; Kenstowicz and Sandalo 2016; Major 1985; Nobre and Ingemann 1987; Wetzels 1992, 2011). In BP, the vowels in stressed syllables have an inventory consisting of seven oral vowels, /i, e, ɛ, a, ɔ, o, u/. Under Degree 1 reduction, only five vowels [i, e, a, o, u] are realized in the surface form, as the missing vowels /ɛ, ɔ/ are realized as [e, o], respectively. For example, in the word 'rodar' /rɔˈdar/ ('to rotate'), the initial /ɔ/ vowel becomes [o] in this context. For Degree 2 reduction, the neutralized mid vowels /e/ and /o/ undergo further reduction to [i] and [u], respectively, and /a/ is realized as [ɐ] in the same position. For example, the second vowel in the word 'roda' /ˈrɔd**a/** ('round') is realized as [ɐ]. Vowel inventories in BP are shown in (1) and example words featuring the different levels of reduction are shown in (2).

Although previous studies generally agree that there are two patterns of reduction, there is no consensus regarding the positions in which Degree 2 reduction occurs. For example, Nobre and Ingemann (1987), Major (1985), and Kenstowicz and Sandalo (2016) demonstrated that Degree 2 reduction is found following primary stressed syllables (i.e., posttonically). Fails and Clegg (1992), on the other hand, suggested that Degree 2 reduction occurs only in *word-final* posttonic position.

(1) Stressed and unstressed vowel inventories of Brazilian Portuguese.

Stressed syllable		Degree 1 reduction		Degree 2 reduction	
i	u	i	u	i	u
e	o	e	o		
ɛ	ɔ			ɐ	
a		a			

(2) Examples of two patterns of vowel reduction in Brazilian Portuguese

Degree 1 reduction (pretonic positions)

Unreduced			Reduced		
bela	[ˈb**ɛ**lɐ]	*'pretty'*	beleza	[b**e**ˈlezɐ]	*'beauty'*
pelo	[ˈp**e**lu]	*'hair'*	pelado	[p**e**ˈladu]	*'naked'*
roda	[ˈr**ɔ**dɐ]	*'wheel'*	rodar	[r**o**ˈdar]	*'to rotate'*
mofo	[ˈm**o**fu]	*'mold'*	mofado	[m**o**ˈfadu]	*'molded'*

Degree 2 reduction (posttonic positions)

Unreduced			Reduced		
duquesa	[duˈk**e**sa]	'*duchess*'	duque	[ˈduk**i**]	'*duke*'
astronomo	[aʃˈtr**o**numu]	*'astronomer'*	astro	[ˈaʃtr**u**]	*'star'*
rodar	[roˈd**a**r]	'*to rotate*'	roda	[ˈrɔd**ɐ**]	'*wheel*'

Barnes (2006) and Crosswhite (2001) both discuss vowel reduction in BP explicitly, and both regard it as similar to the patterns found in Russian. Both authors analyzed Degree 1 reduction as phonological, whereby the contrast between high-mid and low-mid is eliminated, but their treatments of Degree 2 reduction diverge. Crosswhite argues that Degree 2 is like Degree 1, in that it is also phonologically driven (although it is driven by different underlying grammatical pressures), while

Barnes argues it is better described as reflecting phonetic factors, namely duration-dependent phonetic undershoot. In support of his argument, Barnes (2006) notes that some of Major's (1985) observations about Degree 2 reduction are consistent with phonetic vowel reduction in which changes in duration predict greater or lesser reduction. First, edge effects such as phrase-final lengthening can influence the presence of Degree 2 reduction in BP; second, even pretonic vowels (which may bear some level of stress) can show subtle raising in casual and/or fast speech; finally, raising of the nasal mid vowel to high occurs only in fast speech posttonically.

However, Major's observations regarding Degree 2 reduction were impressionistic, and his study was primarily intended to explore phonetic correlates of metrical structure in BP, not vowel reduction per se. Furthermore, although both Barnes (2006) and Crosswhite (2001) discuss and make claims about BP vowel reduction in their cross-linguistic surveys, neither of them present new phonetic data in support of their claims. Only two studies so far seem to present data of this type.

The first of these is a study reported by Fails and Clegg (1992), perhaps the most acoustically comprehensive study on vowel reduction in BP to date. Fails and Clegg presented an acoustic analysis of BP vowels from 10 male BP speakers, reporting first and second formant values for vowels in five different positions: tonic, word-initial pretonic, word-medial pretonic, word-medial posttonic and word-final posttonic. As shown in Table 1, the F1 values of high-mid and low-mid pairs are merged together in all unstressed positions, and the F1 of /e, o, a/ in non-final posttonic syllables are already considerably raised. However, the authors considered the mid vowel raising in non-final positions to be "moving towards a neutralization," and concluded that the three-vowel system that results from Degree 2 reduction can only be observed in word-final position. One additional and

Table 1: Averages of F1 and F2 of BP vowels in each position (based on Fails and Clegg 1992).

	Tonic e.g. /vele'j<u>a</u>r/		Pretonic[a] e.g. /<u>a</u>t<u>a</u>'car/		Word-medial posttonic e.g. /'sab<u>a</u>do/		Word-final posttonic e.g. /'cubic<u>a</u>/	
	F1	F2	F1	F2	F1	F2	F1	F2
i	293	2,149	286	2,120	303	1,942	290	2,039
e	383	1,936	364	1,940	348	1,900		
ɛ	539	1,659						
a	713	1,264	635	1,319	408	1,340	445	1,416
ɔ	545	939	388	779	328	918	329	809
o	399	780						
u	318	896	292	821	303	822		

[a]Fails and Clegg (1992) noted that there were no "appreciable" differences in F1 between word-initial and word-medial pretonic vowels, and they combined the F1 values of the vowels in these positions.

unexpected observation, however, was that F1 was higher for word-medial posttonic /a/ than for word-final posttonic /a/. But because Fails and Clegg did not provide statistical analyses of these patterns, it remains unclear whether such differences were significant.

More recently, Kenstowicz and Sandalo (2016) provided an acoustic analysis of /a/ in four syllable positions (tonic, pretonic, word-medial posttonic, and word-final posttonic) produced by five Brazilian Portuguese speakers. Their results replicated Fails and Clegg's findings, in that pretonic vowels were comparable to tonic vowels in terms of F1, and posttonic vowels showed a significant raising to [ɐ] – suggesting that reduction was likely triggered by a metrical distinction (posttonic versus non-posttonic), not duration. Also replicated was the finding that word-medial posttonic /a/ has a higher F1 than the word-final posttonic /a/. However, they reported that the significant difference in F1 between word-medial and word-final posttonic positions was driven by a durational difference between these two positions – that is, it was likely triggered by duration, not by a categorical contrast related metrical structure. Finally, regression analysis revealed that F1 values for /a/ were, in general, better predicted by prosodic position than by duration. The findings from Kenstowicz and Sandalo (2016) therefore support a phonological rather than phonetic trigger for Degree 2 reduction in BP; one that targets vowels in both word-medial and word-final posttonic syllables, although some amount of phonetic reduction may be present in posttonic syllables as well.

1.3 Research questions and predictions

The disagreement regarding the application of Degree 2 reduction leads us to examine Degree 2 reduction in BP in a wide range of prosodic positions: word-initial pretonic, word-medial pretonic, tonic, word-medial posttonic, and word-final posttonic. In addition, while previous studies are in agreement that Degree 2 reduction is a phenomenon that affects the three vowels /e/, /o/, and /a/, the current study is limited to investigation of /a/, so as to avoid the possibility that speakers' realization of the target vowel is influenced by the orthographic representation.[3] Crucially, the evidence Kenstowicz and Sandalo (2016) provided was insufficient to

3 The Degree 2 reduction of /a/ results in a raising to [ɐ], an allophone of /a/, while the Degree 2 reduction of the mid vowels /e/ and /o/ results in a shift to the high vowels [i] and [u], respectively. Thus, unlike the Degree 2 reduction of /a/, Degree 2 of /e/ and /o/ result in a mismatch regarding orthographic representation. Given that formality influences whether or not speakers apply processes like vowel reduction (Groen 1987), it is possible that participants may produce mid vowels due to influence from spelling, especially in a formal setting like a laboratory. To avoid the possibility of such orthographic influence, only the vowel /a/ was chosen to be a target vowel.

support the phonological status of vowel reduction in BP, since they lacked enough durational variation to examine whether Degree 2 reduction in BP is phonological or phonetic in nature. That is, as discussed in Section 1.1, the role of durational variation is substantial in determining whether vowel reduction in a given language reflects the application of phonological knowledge or a phonetic process.

The goal of the production study presented below is to examine the phonetic and phonological status of vowel reduction in Brazilian Portuguese, with special attention to the influence of duration on the reduction of /a/ to [ɐ] in five prosodic positions: word-initial pretonic, word-medial pretonic, tonic, word-medial posttonic, and word-final posttonic. The research questions are as follows:

1. Is the realization of the vowel /a/ predicted by prosodic (i.e., metrical) position?
2. How do changes in duration (induced via speech rate) affect vowel realization?

Three different predictions can be made regarding the phonetic versus phonological status of Degree 2 reduction in BP. If it is a phonological process, prosodic position should be the primary predictor of quality for /a/, and duration should have little to no effect, as shown schematically in Figure 2A. For example, regardless of the duration of /a/, posttonic /a/ in Figure 2A shows F1 values that range from roughly 380–440 Hz, while F1 values of non-posttonic vowels (pretonic and tonic /a/) lie between 590 and 650 Hz. On the other hand, if it is a phonetic process, the reduction of the low /a/ to mid [ɐ] should be highly dependent on changes in duration, regardless of prosodic position. For example, as illustrated in Figure 2B, when the duration of /a/ is the same across prosodic positions at 110 ms, the F1 values of /a/ in all prosodic positions show a similar locus around 550 Hz. However, if BP has a mixed system of phonological and phonetic reduction, as shown in Figure 2C, changes in duration affect F1 but do not alter the overall pattern of reduction. That is, Degree 2 reduction in BP is mostly phonological, but also features some amount of phonetic reduction. For example, when the duration of /a/ is the same across prosodic positions at 110 ms, the locus of the F1 values varies depending on the prosodic positions: posttonic position is around 500 Hz, while non-posttonic vowels are around 600 Hz. Changes in duration also affect the realization of /a/, but this phonetic reduction occurs within-category, with the categorical effects corresponding to contrasts in prosodic status (posttonic vs. non-posttonic).

2 Methods

2.1 Participants

Eleven speakers of Brazilian Portuguese participated in a production experiment (10 female, 1 male; mean age: 29.5), all of whom originated from southern Brazil.

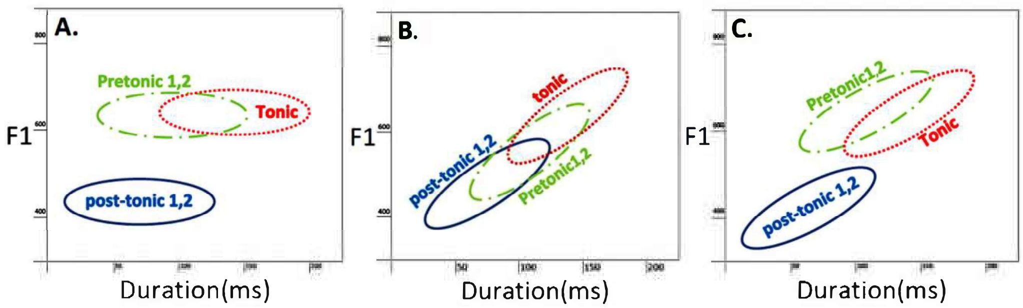

Figure 2: Predictions based on the phonetic versus phonological status of Degree 2 reduction in BP: A) Phonological reduction; B) Phonetic reduction; C) Mixed system. The prosodic positions are coded as follows: *pretonic 1* is for word-initial pretonic, *pretonic 2* is for word-medial pretonic, *tonic* is for tonic, *posttonic 1* is for word-medial posttonic, and *posttonic 2* is for word-final posttonic.

Table 2: Participant information.

Speaker	Gender	Age	Birthplace	Duration of residence in US
1	Female	21	Porto Alegre, RS	5 months
2	Female	28	Rio de Janeiro, RJ	17 months
3	Male	44	Porto Alegre, RS	17 months
4	Female	42	São Paulo, SP	4 months
5	Female	28	São Paulo, SP	17 months
6	Female	30	Rio de Janeiro, RJ	5 months
7	Female	24	São Sebastião do Paraíso, MG	4 months
8	Female	30	São Paulo, SP	3 yrs
9	Female	32	Rio de Janeiro, RJ	2 yrs
10	Female	18	Rio de Janeiro, RJ	1 yrs
11	Female	27	Cascavel, Parana	1 yrs

All participants were living in the United States at the time of the study and were recruited in New York City. Detailed information about the participants is shown in Table 2.

2.2 Speech materials and procedure

Two sets of data were collected in order to examine /a/ produced in a total of five prosodic positions: word-initial pretonic, word-medial pretonic, tonic, word-medial posttonic, and word-final posttonic. One set, List A, consisted of 17 trisyllabic words with ultimate stress (σσσ́; e.g., galopar 'gallop'), in which 14 word-initial pretonic, 6 word-medial pretonic and 17 tonic /a/ tokens were collected. Another, List B, consisted of 19 trisyllabic words with antepenultimate stress (σ́σσ; e.g., pétala 'petal'), in which 7 word-medial posttonic and 14 word-final posttonic /a/ tokens were collected. Examples are shown in Tables 3 and 4, respectively, and the full list of words is shown in Appendix 1, Supplementary Material. The target words were produced in a carrier sentence (*Repita* ___ *de novo* 'repeat ___ again').

As described above, sufficient durational variation is critical to assessing the phonological versus phonetic status of vowel reduction patterns. To induce this variation in the present study, a speech rate manipulation was employed, with speakers being required to produce the carrier sentences at normal, slow and fast rates. To elicit the normal speech rate, participants were to listen to an auditory stimulus which was recorded by a native speaker of Brazilian Portuguese at his normal speech rate. The participants were then instructed to imitate the tempo of the stimulus, while producing a given target sentence. To prevent any priming effect of unintended vowel reduction, the auditory stimuli contained the nonce word /ʃuʃuʃu/, consisting of high back vowels (which do not undergo vowel reduction in BP), as shown in (3). Since the target words consisted of two sets of stimuli with two different stress patterns, the auditory stimuli came in two versions as well, one with final stress (3a) and the other with antepenultimate stress (3b). The elicitation of slow and fast speech rates followed the same process, except that the slow and fast auditory stimuli were created via synthesis from a normal-rate speech sample (1.7 times slower/faster) using PSOLA resynthesis in Praat (Boersma and Weenink 2013). A total of six auditory stimuli were used in the experiment (3 speech rate × 2 stress).

Table 3: Examples of trisyllabic words with ultimate stress (List A: σσσ́).

Word	Word-initial pretonic	Word-medial pretonic	Tonic	Syll #	Stress
galopar	a	o	a	3	Ultimate
paquerar	a	e	a	3	Ultimate
destacar	e	a	a	3	Ultimate

Table 4: Examples of trisyllabic words with antepenult stress (List B: σ́σσ).

Word	Tonic	Word-medial posttonic	Word-final posttonic	Syll #	Stress
pétala	ɛ	a	a	3	Antepenult
dívida	i	i	a	3	Antepenult
bêbada	e	a	a	3	Antepenult

To test the effectiveness of this imitation method, I ran a pilot experiment in Spanish (5 speakers) prior to running the main experiment. The pilot study confirmed that this imitation method can successfully elicit durational variation (See Appendix 2a, Supplementary Material for the results from the pilot study; Also, see Appendix 2b, Supplementary Material for the effectiveness of the elicitation method in yielding durational variation in this experiment).

(3) Examples of auditory and target stimuli

(a)	Auditory stimulus A:	*Repita shushushú de novo*	'Repeat *shushushú* again'
	Target stimulus A:	*Repita separar de novo*	'Repeat *separate* again'
(b)	Auditory stimulus B:	*Repita shúshushu de novo*	'Repeat *shúshushu* again'
	Target stimulus B:	*Repita dúvida de novo*	'Repeat *doubt* again'

The main experiment consisted of three elicitation sessions, based on the different speech rate conditions: 1) slow, 2) normal, and 3) fast. Each session was blocked by two sets: Set A (ultimate stress - σσσ́) and Set B (antepenult stress - σ́σσ), corresponding to the lists. For each session, participants were asked to listen to an auditory stimulus first, and then produce each target sentence three times with the same tempo as the auditory stimulus. The speech materials were recorded using a microphone (Shure SM48) in a soundproof booth. The recorded speech was saved as .wav files with a sampling rate of 44.1 kHz.

2.3 Data analysis

A total of 5,742 vowels were collected: 1,386 initial pretonic /a/ (14 vowels × 3 repetitions × 3 speech rates × 11 speakers), 594 medial pretonic /a/ (6 vowels × 3 × 3 × 11), 1,683 tonic /a/ (17 vowels × 3 × 3 × 11), 693 medial posttonic /a/ (7 vowels × 3 × 3 × 11), and 1,386 final posttonic /a/ (14 vowels × 3 × 3 × 11). Of the 5,742 vowels collected, 280 vowels (5.3%) were discarded due to vowel deletion, disfluency, devoicing or severe creak. Vowel onset and offset were manually marked in Praat based on the onset and offset of the second formant. We obtained the duration of each vowel and the frequency of the first formant at the vowel's midpoint using a script (Crosswhite 2017) in Praat. Given that F2 is highly affected by adjacent segments (e.g., Hillenbrand et al. 2001), the current paper only reported F1 values due to the differences in the target vowels' segmental environment in the stimuli. The raw formant values (in Hz) were transformed to a mel scale and normalized using *z*-scores for each speaker. The raw durational values (in ms) were also normalized using *z*-scores for each speaker.

To examine vowel reduction in unstressed syllables in BP at three different speech rates, we examined (a) the duration of the vowel in each position, (b) the first formant of the vowels in each position, and (c) the correlation between duration and F1 frequency for vowels in each position. Important to keep in mind is that duration was the independent variable of interest here, not the speech rates that were used to manipulate it.

2.4 Statistical models

Statistical analysis was carried out using mixed-effects linear regression with the *lme4* package in R (Bates et al. 2014). Separate models were run with normalized F1 as an outcome variable and Prosodic Position and Duration as fixed-effects predictors of F1. As shown in Table 5, Prosodic Position consisted of five levels, which are coded as follows: *Initial pretonic* is for word-initial pretonic, *Medial pretonic* is for word-medial pretonic, *Tonic* is for tonic, *Medial posttonic* is for word-medial posttonic, and *Final posttonic* is for word-final posttonic. This coding for Prosodic Position applies also for the figures and the tables in the paper. Speaker and Item were added in the models as random-effects, and models were constructed in an incremental fashion by adding fixed-effects factors that represented simple effects and interactions. A similar approach was used for testing the effects of Prosodic Position on Duration. Multiple paired analyses were carried out using the *glht* function in the *multcomp* package in R which applies the *Tukey* method to adjust *p*-values for multiple comparisons (Bretz et al. 2010; Hothorn et al. 2008). The *glht* function takes a fitted response model and performs all pairwise comparisons between the five Prosodic Positions.

Table 5: Coding for prosodic positions.

Variable name	Prosodic position	Example	Stress
Initial pretonic	Word-initial pretonic (**σ**σσ́)	/**a**taˈcar/	Ultimate
Medial pretonic	Word-medial pretonic (σ**σ**σ́)	/at**a**ˈcar/	Ultimate
Tonic	Tonic (σσ**σ́**)	/ataˈc**a**r/	Ultimate
Medial posttonic	Word-medial posttonic (σ́**σ**σ)	/ˈpɛt**a**la/	Antepenult
Final posttonic	Word-final posttonic (σ́σ**σ**)	/ˈpɛtal**a**/	Antepenult

3 Results

3.1 Normal speech rate

Before presenting vowel reduction at all speech rates, which involve maximal durational variation, I first examine the vowel reduction at the normal speech rate which shows how intrinsic/natural variation affects F1 realization of vowels. The boxplots in Figure 3 illustrate the distributions of normalized duration and F1 for /a/ in the five prosodic positions at normal speech rate. Importantly, Figure 3A shows that the duration of pretonic vowels (*Initial pretonic* and *Medial pretonic*) and posttonic vowels (*Medial posttonic* and *Final posttonic*) are comparable, while Figure 3B illustrates that their F1 values are not; posttonic vowels were realized with a much lower F1 than pretonic and tonic vowels.

This pattern is also apparent in Figure 4, which plots F1 as a function of duration (bottom left), as well as two density plots showing the distributions of Duration (top left) and F1 (bottom right). The scatter plot also contains correlation coefficients (r) and corresponding p-values for the relationship between F1 and duration in each prosodic position, based on simple linear models. Notably, categorical separation of F1 values is apparent in relation to prosodic position; F1 values for posttonic (including final and medial posttonic) and non-posttonic (including initial and medial pretonic, and tonic) show relatively clearly separated clusters in the scatterplot – and clearly complementary distribution in the density plot for F1 values. On the other hand, the durations of /a/ in atonic positions show

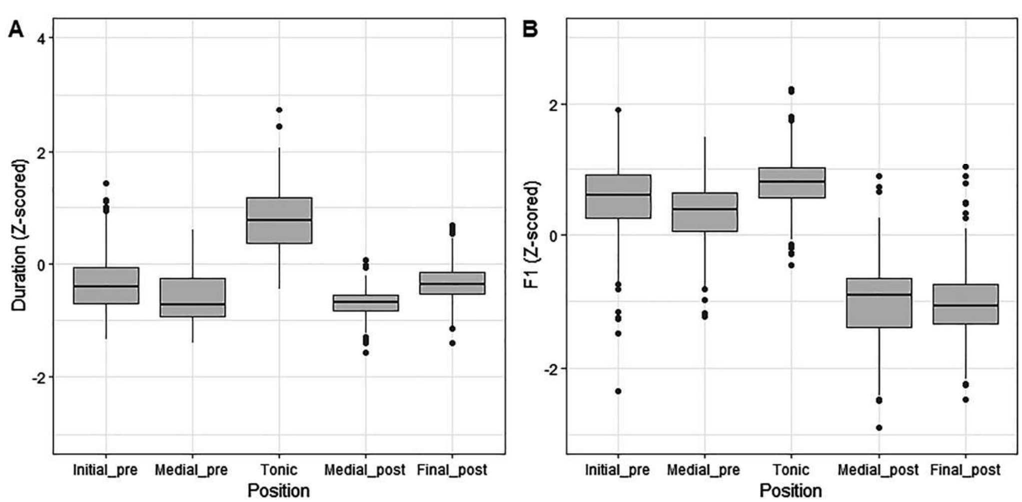

Figure 3: Duration (A) and F1 (B) of the vowel /a/ in the five prosodic positions at normal speech rate.

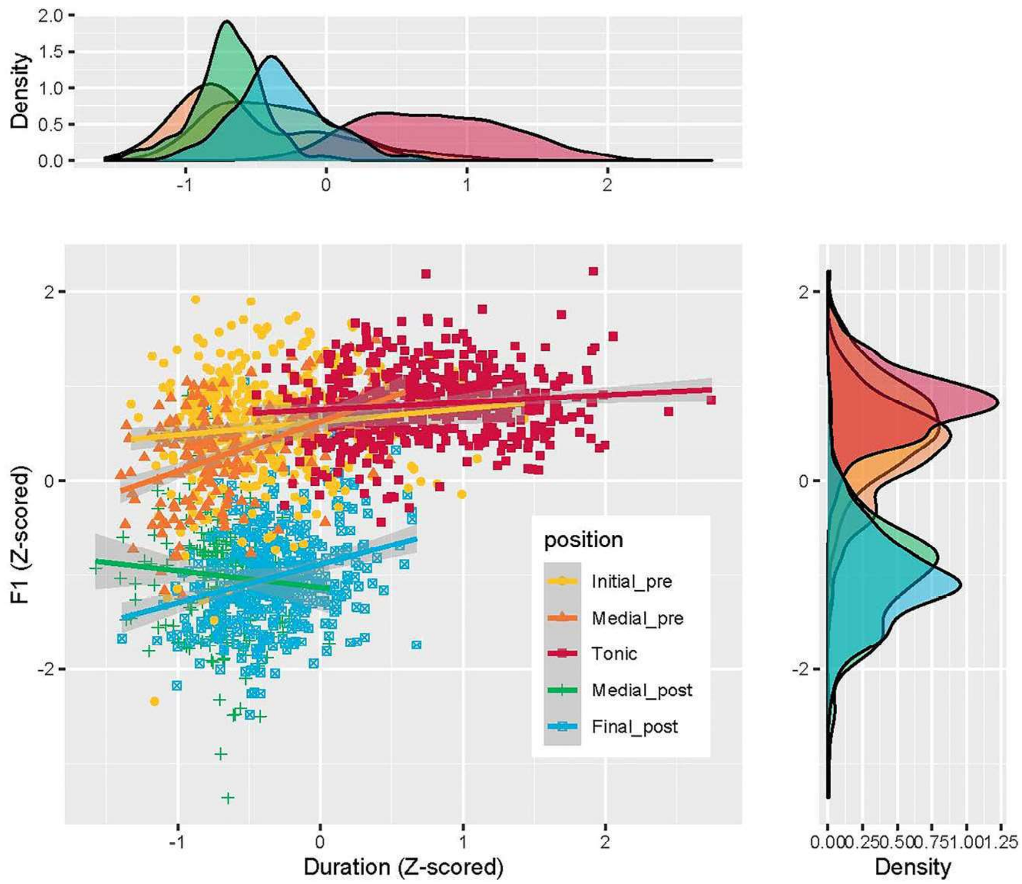

Figure 4: Normal speech rate: Scatter plot of F1 as a function of Duration & density plots of Duration (top left) and F1 (bottom right). To add regression lines, the function *geom_smooth()* was used with the argument *method* = l*m*. Also, the function *stat_cor()* was used to add correlation coefficients (*r*) with *p*-values to the scatter plots.

considerable overlap. Furthermore, simple tests of correlations shows that there is a weak but significant relationship between Duration and F1 at in at least initial pretonic ($p < 0.05$), medial pretonic ($p < 0.001$), tonic ($p < 0.05$), and final posttonic ($p < 0.001$) positions.

To assess the statistical significance of these simple correlations more rigorously, linear mixed effects regression was used to model these data (with models fitted for maximum likelihood; for additional detail, see Section 2.4). As shown in Table 6, fitted mixed-effects models with F1 as the outcome variable revealed that the addition of Duration significantly improved the baseline model, which contains only the random effects of subject and item ($\chi^2 = 207.87$, $p < 0.001$). Crucially, however, when Prosodic Position is added to the model, it results in a significant improvement to model fit relative to the Duration-only model ($\chi^2 = 147.76$, $p < 0.001$). This indicates that Prosodic Position accounts for the differences in F1 above and beyond what duration does. Furthermore, adding an interaction term for Prosodic Position × Duration also improved model fit ($\chi^2 = 61.75$, $p < 0.001$), suggesting that the effect of Duration may not be uniform across all five prosodic positions, consistent with the pattern in Figure 4. In addition, as shown in Table 7, fitted mixed-effects models with Duration as the outcome variable revealed that there was a significant effect of Prosodic Position on Duration ($\chi^2 = 1{,}647.7$, $p < 0.001$).

Further analyses using post-hoc testing have been carried out to compare each prosodic position with respect to F1 (Table 8) and Duration (Table 9). In line with Figure 3, posttonic vowels (*Medial posttonic* and *Final posttonic*) were significantly different from non-posttonic vowels (*Initial pretonic*, *Medial pretonic* and *tonic*) in terms of F1 (Table 8). On the other hand, as shown in Table 9, the durations of medial pretonic and medial posttonic vowels (*Medial pretonic* vs. *Medial posttonic*), as well as initial pretonic and final posttonic (*Initial pretonic* vs. *Final posttonic*), were not significantly different from each other. That is, even though the durations of pretonic and posttonic vowels were comparable, their F1 values differed significantly based on the prosodic position they occurred in. This

Table 6: Normal speech rate (F1 as dependent variables): Results of mixed model comparisons using likelihood ratio tests. The log-likelihood comparisons illustrate the result of comparison between each model and the one immediately above it in the table. AIC (Akaike information criterion) values in boldface indicate better fit. '1' indicates the intercept in the model. VIF (variance inflation factor) values of the variables in the last model are as follows: Prosodic Position (1.527), Duration (8.170), and interaction (1.982), which are calculated using the *vif* function in the R package *car*.

LME model comparison (F1~)	Df	AIC	logLik	χ^2	Pr(>χ^2)
1 + (1|Speaker) + (1|item)	4	2,743.4	−1,367.7	NA	NA
1 + Duration + (1|Speaker) + (1|item)	5	**2,537.6**	−1,263.8	207.87	<0.001
1 + Duration + Position + (1|Speaker) + (1|item)	9	**2,397.8**	−1,189.9	147.76	<0.001
1 + Duration * Position + (1|Speaker) + (1|item)	13	**2,344.1**	−1,159.0	61.752	<0.001

Table 7: Normal speech rate (Duration as dependent variables): Results of mixed model comparisons using likelihood ratio tests. The log-likelihood comparisons illustrate the result of comparison between each model and the one immediately above it in the table. AIC (Akaike information criterion) values in boldface indicate better fit. '1' indicates the intercept in the model.

LME model comparison (Duration~)	Df	AIC	logLik	χ^2	Pr(>χ^2)
1 + (1|Speaker) + (1|item)	4	3,520.7	−1,756.35	NA	NA
1 + Position + (1|Speaker) + (1|item)	8	**1,881.0**	−932.51	1,647.7	<0.001

dependence on prosodic position rather than duration alone suggests that this variation in F1 primarily reflects a phonological process.

In addition, another interesting result from Table 9 is that initial pretonic vowels and final posttonic vowels were significantly longer than medial pretonic vowels and medial posttonic vowels, respectively (*Initial pretonic > Medial pretonic; Final posttonic > Medial posttonic*). This suggests edge effects; durational variation reflecting initial strengthening and final lengthening seem to occur. The post-hoc testing also illustrated that there were significant differences in F1

Table 8: Normal speech rate: Multiple Comparisons of Prosodic Position in terms of F1. Multiple Comparisons of Means: Tukey Contrasts. Fit: lmer(formula = F1 ~ Position * Duration + (1|Speaker) + (1|Item), data = normal). Each Linear Hypothesis shows a comparison contrast for prosodic position relative to a baseline contrast.

Linear hypotheses			Estimate	Std.Error	Pr(>|*z*|)
Initial pretonic	==	Medial pretonic	−0.0167	0.074	>0.1
Initial pretonic	==	Tonic	0.1261	0.046	<0.05
Initial pretonic	==	Medial posttonic	−1.2159	0.146	<0.001
Initial pretonic	==	Final posttonic	−1.5607	0.097	<0.001
Medial pretonic	==	Tonic	0.1429	0.075	>0.1
Medial pretonic	==	Medial posttonic	−1.1992	0.156	<0.001
Medial pretonic	==	Final posttonic	−1.5439	0.113	<0.001
Medial posttonic	==	Tonic	−1.3421	0.147	<0.001
Final posttonic	==	Tonic	−1.6868	0.099	<0.001
Final posttonic	==	Medial posttonic	−0.3447	0.131	<0.1

Table 9: Normal speech rate: multiple comparisons of prosodic position in terms of duration. Multiple comparisons of means: Tukey contrasts. Fit: lmer(formula = Duration ~ Position + (1|Speaker) + (1|Item), data = normal). Each Linear Hypothesis shows a comparison contrast for prosodic position relative to a baseline contrast.

Linear hypotheses			Estimate	Std.Error	Pr(>|*z*|)
Initial pretonic	==	Medial pretonic	−0.2936	0.040	<0.001
Initial pretonic	==	Tonic	1.0826	0.026	<0.001
Initial pretonic	==	Medial posttonic	−0.4127	0.072	<0.001
Initial pretonic	==	Final posttonic	−0.0113	0.064	>0.1
Medial pretonic	==	Tonic	1.3762	0.037	<0.001
Medial pretonic	==	Medial posttonic	−0.1191	0.076	>0.1
Medial pretonic	==	Final posttonic	0.2823	0.069	<0.001
Medial posttonic	==	Tonic	−1.4953	0.071	<0.001
Final posttonic	==	Tonic	−1.0939	0.063	<0.001
Final posttonic	==	Medial posttonic	0.4014	0.055	<0.001

between tonic and initial pretonic vowels (*Tonic* vs. *Initial pretonic*), as well as a marginally significant difference between medial and final posttonic vowels (*Medial posttonic* vs. *Final posttonic*; See Table 8). Given that each pair also showed a significant difference in duration, however, the difference in F1 in these positions can be explained by durational differences – and thus phonetic undershoot.

In sum, the results thus far suggest that Degree 2 reduction is predominantly phonological, showing a two-way categorical contrast between posttonic and non-posttonic vowels, similar to the results from Kenstowicz and Sandalo (2016). However, the current study also found that changes in duration affect the realization of /a/ within each respective boundary of phonological reduction (posttonic vs. non-posttonic). These results suggest that Degree 2 reduction in BP also reflects a phonetic process, though the effect of duration on F1 was weak and inconsistent across prosodic positions. One possibility that needs to be ruled out is that these patterns are in part due to insufficient variation in duration, since only variation associated with normal speech rate was explored thus far. In the following section, the present study examined all speech rates to confirm the status of Degree 2 reduction in BP in the presence of greater variation in duration.

3.2 All speech rates

As can be seen in Figure 5, the basic pattern just described above for words produced at a normal speech rate also held for slow and fast speech rates, as shown in Figure 5. To explore the effect of duration on vowel reduction in BP, we therefore examined the relation between duration and F1, collapsing for speech rates. Figure 6 shows a scatter plot of F1 as a function of duration (bottom left) with *r* values and *p*-values for the correlation between the two in each prosodic position. Additionally, two density plots for Duration (top left) and F1 (bottom right) are also included in Figure 6. Similar to Figure 4, F1 values in Figure 6 show a categorical separation between posttonic and non-posttonic, while the duration of /a/ in atonic positions overlaps strongly. Furthermore, the correlation between Duration and F1 was consistent across prosodic positions ($p < 0.001$ for all positions). However, even when vowel duration is quite long, vowels in posttonic positions rarely reach the F1 values that vowels in pretonic and tonic positions do, suggesting that their underlying phonological targets differ from the non-posttonic vowels.

Tables 10 and 11 present the results of the mixed-effects models (fitted by maximum likelihood) for F1 and Duration measures at all speech rates, respectively. Much as for normal speech rate, analyses that collapsed for speech rate showed that Duration explains variation in F1, but Prosodic Position is a significant

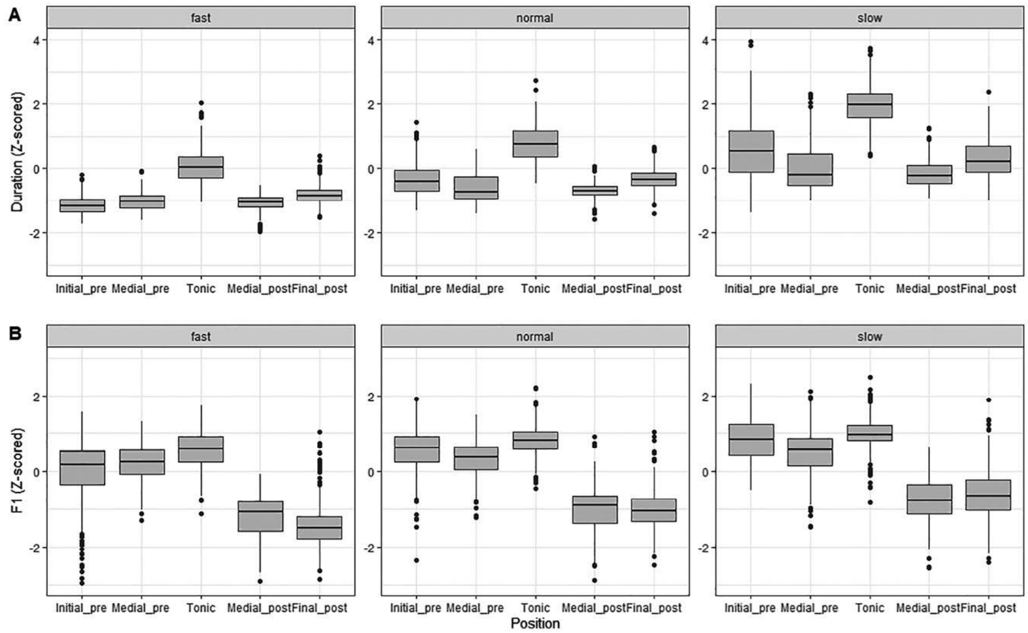

Figure 5: Duration (A) and F1 (B) for /a/ by prosodic position for three different speech rates.

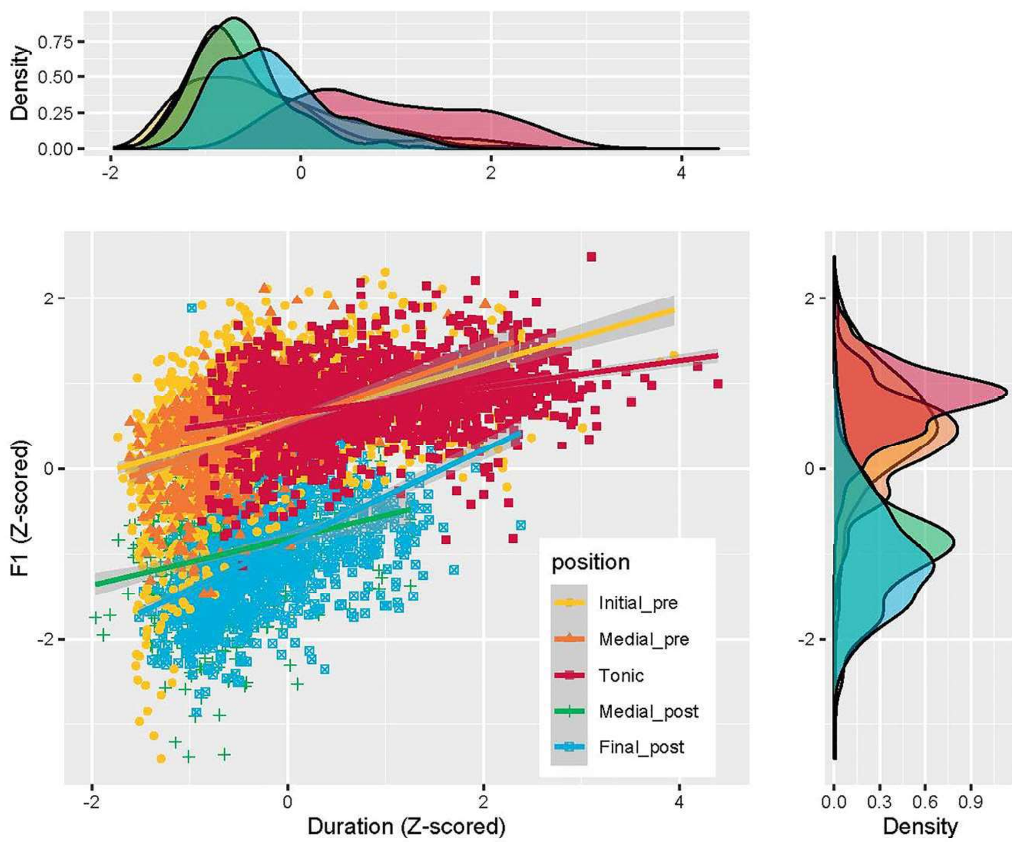

Figure 6: All speech rates: Scatter plot of F1 as a function of Duration & density plots of Duration (top left) and F1 (bottom right). To add regression lines, the function *geom_smooth()* was used with the argument *method* = *lm*. Also, the function *stat_cor()* was used to add correlation coefficients (*r*) with *p*-values to the scatter plots.

predictor above and beyond Duration. In addition, there was a significant interaction between these two factors, suggesting that the effect of Duration may not be uniform across all five prosodic positions as well. Fitted mixed-effects models with Duration as the outcome variable also revealed that there was a significant effect of Prosodic Position on Duration.

As shown in Tables 12 and 13, post-hoc testing revealed that posttonic vowels are significantly different from non-posttonic vowels in terms of F1 ($p < 0.001$ for all pairs), while the duration of pretonic and posttonic vowels are comparable ($p > 0.1$ for both *Final posttonic* vs. *Initial pretonic and Medial posttonic* vs. *Medial pretonic* comparisons). Finally, pretonic and posttonic vowels at word boundaries showed significantly longer durations than those in medial positions, indicating the presence of initial strengthening and final lengthening even when speech rate is collapsed (Table 11).

In summary, then, the relation between F1 and duration when all speech rates were combined was consistent with the analysis, above, that considered only the normal speech rate. This suggests the categorical distribution in F1 values related to prosodic position was not due to limited durational variation in the normal

Table 10: Normal speech rates (F1 as dependent variables): Results of mixed model comparisons using likelihood ratio tests. The log-likelihood comparisons illustrate the result of comparison between each model and the one immediately above it in the table. AIC (Akaike information criterion) values in boldface indicate better fit. '1' indicates the intercept in the model. VIF (variance inflation factor) values of the variables in the last model are as follows: Prosodic Position (1.165), Duration (2.125), and interaction (1.338), which are calculated using the *vif* function in the R package *car*.

LME model comparison (F1~)	Df	AIC	logLik	χ^2	Pr(>χ^2)
1 + (1|Speaker) + (1|item)	4	10,262.4	−5,127.2	NA	NA
1 + Duration + (1|Speaker) + (1|item)	5	**8,963.5**	−4,476.8	1,300.9	<0.001
1 + Duration + Position + (1|Speaker) + (1|item)	9	**8,806.5**	−4,394.3	165	<0.001
1 + Duration * Position + (1|Speaker) + (1|item)	13	**8,554.3**	−4,264.1	260.27	<0.001

Table 11: All speech rates (Duration as dependent variables): Results of mixed model comparisons using likelihood ratio tests. The log-likelihood comparisons illustrate the result of comparison between each model and the one immediately above it in the table. AIC (Akaike information criterion) values in boldface indicate better fit. '1' indicates the intercept in the model.

LME model comparison (Duration~)	Df	AIC	logLik	χ^2	Pr(>χ^2)
1 + (1|Speaker) + (1|item)	4	14,795	−7,393.4	NA	NA
1 + Position + (1|Speaker) + (1|item)	8	**12,845**	−6,414.7	1,957.5	<0.001

Table 12: All speech rates: multiple comparisons of prosodic position in terms of F1. Multiple comparisons of means: Tukey contrasts. Fit: lmer(formula = F1 ~ Position * Duration + (1|Speaker) + (1|Item), data = all). Each Linear Hypothesis shows a comparison contrast for prosodic position relative to a baseline contrast.

Linear hypotheses			Estimate	Std.Error	Pr(>|*z*|)
Initial pretonic	==	Medial pretonic	−0.0711	0.038	>0.1
Initial pretonic	==	Tonic	0.0532	0.025	>0.1
Initial pretonic	==	Medial posttonic	−1.1305	0.098	<0.001
Initial pretonic	==	Final posttonic	−1.5367	0.090	<0.001
Medial pretonic	==	Tonic	0.1242	0.037	<0.01
Medial pretonic	==	Medial posttonic	−1.0595	0.102	<0.001
Medial pretonic	==	Final posttonic	−1.4656	0.094	<0.001
Medial posttonic	==	Tonic	−1.1837	0.099	<0.001
Final posttonic	==	Tonic	−1.5898	0.090	<0.001
Final posttonic	==	Medial posttonic	−0.4061	0.058	<0.001

Table 13: All speech rates: multiple comparisons of prosodic position in terms of duration. Multiple comparisons of means: Tukey contrasts. Fit: lmer(formula = Duration ~ Position + (1|Speaker) + (1|Item), data = all). Each Linear Hypothesis shows a comparison contrast for prosodic position relative to a baseline contrast.

Linear hypotheses			Estimate	Std.Error	Pr(>|*z*|)
Initial pretonic	==	Medial pretonic	−0.2479	0.046	<0.001
Initial pretonic	==	Tonic	1.1950	0.030	<0.001
Initial pretonic	==	Medial posttonic	−0.3882	0.073	<0.001
Initial pretonic	==	Final posttonic	0.0115	0.064	>0.1
Medial pretonic	==	Tonic	1.4429	0.042	<0.001
Medial pretonic	==	Medial posttonic	−0.1403	0.079	>0.1
Medial pretonic	==	Final posttonic	0.2594	0.071	<0.01
Medial posttonic	==	Tonic	−1.5833	0.072	<0.001
Final posttonic	==	Tonic	−1.1835	0.063	<0.001
Final posttonic	==	Medial posttonic	0.3997	0.060	<0.001

speech rate. And while some additional variation in F1 does seem to be related directly to duration, this does not alter the overall effect of the posttonic versus non-posttonic distinction. Taken together, the pattern that therefore emerges for BP is one of a mixed system of phonological and phonetic reduction, as illustrated earlier in Figure 2C.

3.3 Individual variation

As discussed in Sections 3.1 and 3.2, F1 was overall much better predicted by Prosodic Position than by duration, although longer vowel duration was associated with a higher F1 in a statistically significant way. However, the analysis on individual variation revealed an interesting behavior among BP speakers. Unlike all other speakers who displayed two phonological categories in the Degree 2 reduction (posttonic vs. non-posttonic), speaker 5 does not show a large categorical raising of /a/ in any syllable. Instead, when the duration of pretonic vowels (*Initial pretonic* and *Medial pretonic*) and posttonic vowels (*Medial posttonic* and *Final posttonic*) are comparable, the F1 realization of /a/ in these positions is also similar, as shown in Figure 7. Furthermore, at a slow speech rate, the final posttonic /a/ vowels (*Final posttonic*) showed a similar F1 realization as the tonic /a/. This pattern is also evident in Figure 8, which illustrates F1 as a function of duration (bottom left) as well as distributions of Duration (top left) and F1 (bottom right). F1 as well as duration data from speaker 5 exhibits a severe overlap across the five prosodic positions, making all atonic syllables for her more like pretonic syllables for the other speakers. For example, when the duration of /a/ is the same across prosodic positions at 1.5 (*z*-scored), the F1 values of /a/ in all prosodic positions show a similar locus around 1 (*z*-scored). This observation suggests that the Degree 2 reduction of speaker 5 may not (yet) be a phonological process for all

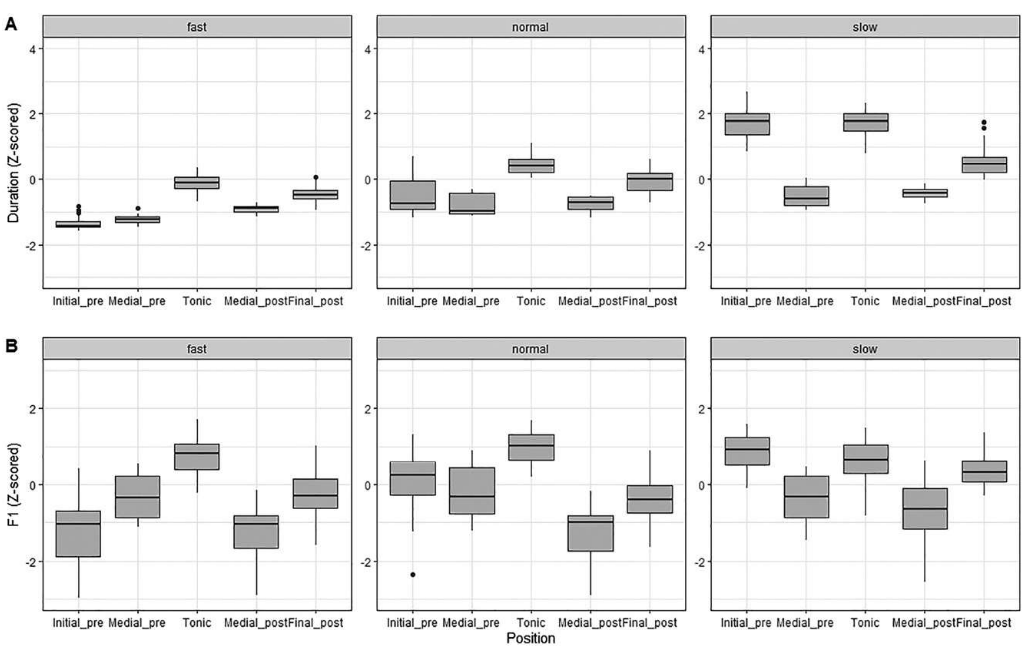

Figure 7: Duration (A) and F1 (B) for /a/ by prosodic position for speaker 5.

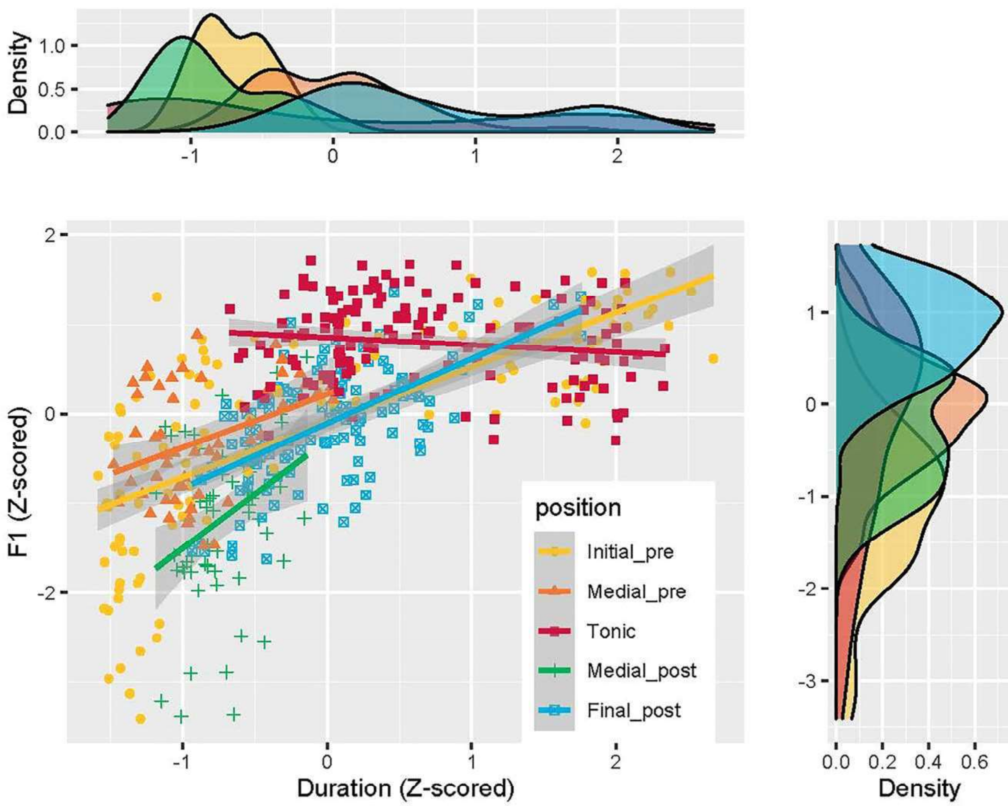

Figure 8: BP5: Scatter plot of F1 as a function of Duration & density plots of Duration (top left) and F1 (bottom right). To add regression lines, the function *geom_smooth()* was used with the argument *method* = *lm*. Also, the function *stat_cor()* was used to add correlation coefficients (*r*) with *p*-values to the scatter plots.

speakers of BP. Instead, the Degree 2 reduction of speaker 5 seems to be duration-dependent phonetic reduction. Furthermore, even among the speakers who showed phonological behavior, the sensitivity to duration also varied (See Appendix 3).

4 Discussion

4.1 Overview

The experiment presented above sought to better understand the phonological and phonetic status of vowel reduction in Brazilian Portuguese (BP). In particular, it tested whether the realization of the vowel /a/ in BP is better predicted by prosodic position (a phonological variable) or by duration (a phonetic variable). This question was asked about vowels in five prosodic positions: word-initial pretonic, medial pretonic, tonic, medial posttonic, and final posttonic. Moreover, to ensure that there was sufficient durational variation to see its effects, speakers produced these vowels at three different speech rates.

The results revealed that Prosodic Position explains differences in F1, far above and beyond what duration does. For example, it was revealed that, though the duration of pretonic and posttonic vowels were comparable, posttonic vowels were significantly higher than pretonic (and tonic) vowels in terms of vowel height. This pattern holds for normal speech rate as well as all speech rates. This indicates that Degree 2 reduction targets posttonic syllables regardless of their duration. These findings serve as good evidence for a systematic and, crucially, categorical relation between vowel reduction and prosodic position, suggesting a primarily phonological status for vowel reduction in BP. However, there were also weak but significant positive correlations observed between F1 and duration for all prosodic positions, indicating that phonetic reduction is also present. Thus, Degree 2 reduction in BP reflects primarily phonological patterning, with some additional phonetic reduction – i.e., a mixed system, as described in Section 1.3 and illustrated in Figure 2C.

4.2 Phonetic and phonological vowel reduction in BP

Previous studies have discussed the distinction and relation between phonology and phonetics. The prevailing assumption is that phonology and phonetics form two separate entities, wherein phonology involves discrete and categorical units, whereas phonetics deals with more gradient and continuous shifts (e.g., Cohn 1998, 2007; Keating 1996; Zsiga 1995). In keeping with this, in this paper, phonological reduction is defined as a categorical change leading to smaller inventories of vowels in unstressed syllables, while phonetic reduction is defined as a gradient change in vowel quality in the context of durational shortening.

However, teasing apart phonetics and phonology is often not straightforward, since they often produce similar results (e.g., phonological and phonetic reduction result in reduced duration and qualitative changes in vowels). This picture is even more complicated with the phonologization of phonetic phenomena over time. Moreover, recent studies have suggested a blurring of the distinction between phonetics and phonology – that is to say, these two fields might not exist in as much of a discrete sense as previously thought. For example, Pycha (2009) has shown that phonological lengthening (via gemination) and phonetic lengthening (via phrase final lengthening) of affricates in Hungarian produced "roughly equivalent degrees of overall change." However, they increased the duration of affricates in different ways in that phonological lengthening targets the stop closure portion of affricates, while phonetic lengthening targets the frication portion. She argued that defining phonology as categorical and phonetics as gradient might oversimplify the nature of phonology and phonetics. However, this is not necessarily the case. Given her experimental design where phonetic lengthening is represented by phrase final lengthening, it is not surprising that phrase final lengthening leads to a similar degree of overall durational change compared to phonological lengthening (See Gósy and Krepsz 2018; Hockey and Fagyal 1998, 1999 for more discussion on phrase final lengthening in Hungarian). However, that does not necessarily negate that the essence of phonology and phonetics is categorical and gradient, respectively. If she were to examine the phonetic lengthening of Hungarian affricates in a different setting, e.g., speech rate modulation, this would yield a gradient result.

The current paper argues for the aforementioned stance with regard to phonological and phonetic reduction – that is, phonology being categorical in nature and phonetics being gradient. It shows that the realization of the vowel /a/ in BP is predicted by prosodic position (a phonological variable) as well as duration (a phonetic variable), reflecting a mixed system of phonological and phonetic reduction. Indeed, any languages which exhibit phonological reduction would have this mixed system to a certain degree, since durational variation is effectively inevitable. A recent study by Nadeu (2016) reported that Catalan, which exhibits phonological reduction, also undergoes phonetic reduction. In particular, phonologically unreduced vowels in unstressed positions in Catalan showed shorter duration and more centralized vowel space than stressed vowels. Such a mixed system is expected to be inherently present in other languages, and it would logically follow that it is also true for Degree 2 reduction in BP. For the foregoing reason, phonetic undershoot which is governed by such biomechanical constraints is expected to a certain degree to be present in virtually all languages, and the phonological reduction alone model, as shown schematically in Figure 2A, is hardly expected in any language.

4.3 Other vowels in Brazilian Portuguese

The current study used the vowel /a/ as a test vowel to examine the phonetic and phonological status of Degree 2 reduction in Brazilian Portuguese. We chose the vowel /a/ to avoid the possibility of the speakers' realization of the target vowel being influenced by the orthographic representation. As discussed in Section 1.2, however, Degree 2 reduction also targets the mid vowels /e/ and /o/, resulting in further reduction to [i] and [u], respectively.

Major's (1985) impressionistic observations about Degree 2 reduction provide some insight into predicting whether the mid vowel raising as part of Degree 2 reduction would be phonetic, phonological, or both in nature. He argued that Brazilian Portuguese bears two degrees of phonological stress, which governs the degree of vowel reduction. He demonstrated that Degree 1 reduction occurs in a pretonic syllable, while Degree 2 reduction is found in a posttonic syllable. However, he also observed that /e/ and /o in pretonic positions can show subtle raising in casual and/or fast speech. In addition, when a phrase final syllable is substantially lengthened, increased duration can affect the realization of underlying /e/ and /o/ vowels as well.

Although his observation is impressionistic (data from three speakers and lack of statistical analysis), his observation regarding raising of /e/ and /o/ resembles our findings about raising of /a/, in that the reduction is generally governed by metrical structure while showing some effect of duration on F1 realization of vowels. Taking this into consideration, the results the paper found for /a/ can be generalized into the other vowels in Degree 2 reduction, which would represent a mixed system of phonological and phonetic reduction.

4.4 Implications for sound change

The results of the study presented above suggest Degree 2 reduction in BP reflects a mixed system of phonological and phonetic reduction. However, one speaker (Speaker 5) who participated in our study exhibited a pattern that suggests only phonetic reduction, as F1 values appear to be better predicted by duration than prosodic position. It is possible that some speakers like speaker 5 lack phonological reduction in their grammar, and instead apply only duration/effort-dependent reduction. Such speaker variation raises the possibility that Brazilian Portuguese may be in a state of diachronic change whereby most speakers, but not all, have phonologized what was once only a phonetic process (See Barnes 2006, 2007; Blevins 2004, 2006; for further discussion).

This interpretation is consistent with the scenario for the development of /a/ in BP schematized in Figure 9. Possibly, at some early stage, BP featured little to no reduction (Stage 1). More crucially, however, is a subsequent stage during which significant duration-dependent variation did exist, with phonetic undershoot as its mechanism (Stage 2). Over time, speakers and listeners reinterpreted that undershoot as intended reduction in metrically weak syllables, phonologizing the reduction (Stage 3). The scenario in Figure 9 thus describes the progression for most of the speakers in the present study, with only speaker 5 not participating in the change.

This diachronic sound change of Degree 2 reduction is further supported by the literature on the history of Brazilian Portuguese. While it is controversial when Brazilian Portuguese established Degree 2 reduction as a phonological process, Naro (1971) noted that /e/ and /o/ were often realized as slightly raised in unstressed final positions in European and Brazilian Portuguese in the sixteenth century. Crucially, however, /e/ and /o/ were never reported to exhibit a full raising to [i] and [u], respectively. This suggests that Degree 2 reduction was once only a phonetic process in Brazilian Portuguese.

An alternative scenario is one with the opposite directionality. In that scenario, speaker 5 is instead an innovator in change, decoupling quality from metrical structure and interpreting it as strictly duration dependent. However, further study with a greater number of speakers (and perhaps, varieties) would be necessary to understand the role of such variation in diachronic change.

4.5 Implications for metrical structure

Some details of the present study's findings about vowel reduction may also provide some insight into the metrical structure of BP. In particular, they seem to support a tertiary stress system. Kenstowicz and Sandalo (2016), for example, proposed that Degree 2 reduction reflects metrical structure in BP. They argued that Degree 2 reduction on posttonic syllables is attributable to lack of any stress in these positions. As shown in Figure 10A, they assume that the pretonic syllable carries secondary stress, with no stress on the posttonic syllable in paroxytones (σσ́σ). In proparoxytones (σ́σσ), however, both posttonic syllables lack any stress, as shown in Figure 10B. In the case of oxytones (σσσ́), previous studies argued that pretonic syllables do not carry the same level of prosodic prominence (Arantes and Barbosa 2006; Moraes 1998). In particular, they proposed that a secondary stress would fall on each even pretonic syllable, counted from right to left, starting from the primary stressed one, characterizing a strong/weak alternation (trochaic feet). That is, in the case of trisyllabic words with ultimate stress (σσσ́), the initial pretonic has a secondary stress and the medial pretonic has no stress, as shown in Figure 10C.

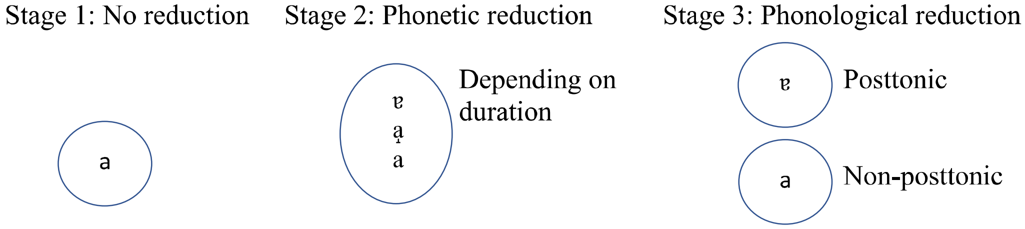

Figure 9: Hypothesized development of the distribution of /a/ in BP.

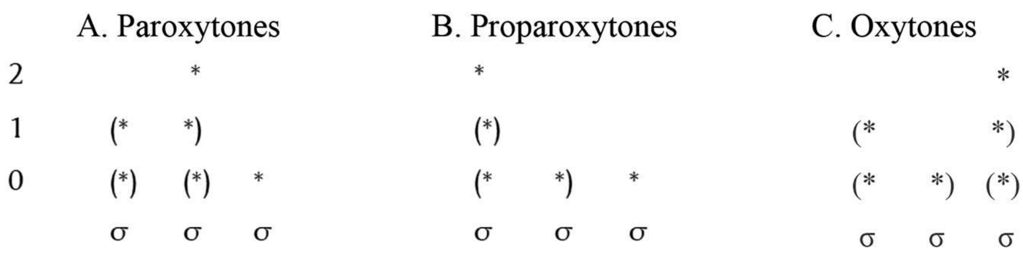

Figure 10: Metrical structures in BP: A. Paroxytones, B. Proparoxytones, and C. Oxytones (A & B are adapted from Kenstowicz and Sandalo 2016; C from Moraes 1998).

The proposed structure of oxytones (σσσ́) in Figure 10C, however, gives rise to some issues regarding Degree 2 reduction. Assuming that Degree 2 reduction targets syllables with no stress, the word-medial pretonic vowel in Figure 10C is expected to undergo Degree 2 reduction. However, this is not consistent with the current findings, since pretonic vowels did not undergo Degree 2 reduction. Positing the presence of secondary stress for both initial and medial pretonic vowels would descriptively solve the problem (See Major 1985 for further discussion), but would be highly inconsistent with previous work on BP metrical phonology (Arantes and Barbosa 2006; Moraes 1998), and metrical theory more generally (e.g., Hayes 1995).

This issue can be resolved if we posit that Degree 2 reduction in BP targets posttonic vowels, and it does not reflect metrical structure in BP. However, if it does, as Kenstowicz and Sandalo (2016) argued, it needs to be explained why word-medial pretonic vowels do not undergo Degree 2 reduction. I propose that the medial pretonic syllable bears a tertiary stress, and Degree 2 reduction targets syllables with no stress. That is, the medial pretonic syllable in Figure 10C is no longer a target of Degree 2 reduction since it bears a tertiary stress. If degree 2 reduction reflects metrical structure in BP, the argument for tertiary stress is necessary since without positing the tertiary stress, the previously proposed metrical structure would incorrectly predict Degree 2 reduction of word-medial pretonic vowels. However, to support this proposal, a future study would be necessary to investigate whether vowels in the medial pretonic position in BP have other acoustic correlates of tertiary stress.

5 Summary and conclusion

Following the argument regarding phonological versus phonetic reduction established in Crosswhite (2001) and Barnes (2002, 2006, 2007), the present study hypothesized that phonological reduction is predictive of no categorical change of vowels in response to changes in duration, while phonetic undershoot is clearly predictive of a greater/lesser reduction depending on decreased/increased duration. This allows us to directly test whether vowel reduction in a given language is phonetic, phonological, or both in nature. In the current study, to investigate the phonetic versus phonological status of vowel reduction in Brazilian Portuguese, we examined the influence of duration on F1 realization of /a/ in five prosodic positions: word-initial pretonic, word-medial pretonic, tonic, word-medial posttonic, and word-final posttonic. The current work confirmed previous findings from Kenstowicz and Sandalo (2016) in that Degree 2 reduction showed a two-way categorical distinction between posttonic and non-posttonic vowels, suggesting that it is predominantly phonological. However, we further found that changes in duration significantly affect the F1 realization of /a/, while keeping the categorical reduction pattern. That is, this phonetic reduction locally occurs within each respective boundary of phonological reduction. Taken together, these findings suggest that vowel reduction in BP reflects a mixed system; syllables undergo categorical reduction based on metrical structure (phonological reduction), while all syllables – but especially unstressed syllables – are gradiently undershot in relation to duration (phonetic reduction). The results of this study are important both for the analysis of BP vowels, and for discussion on the interface between the phonetic and phonological components of grammar more generally.

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