Acoustic analysis of European Portuguese uvular [χ, ʁ] and voiceless tapped alveolar [ɾ̥] fricatives

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In a study of European Portuguese fricatives it was noted that /ʀ, ɾ/ were often realized as [χ, ʁ, ɾ̥], which are, respectively, unvoiced and voiced uvular fricative, and voiceless tapped alveolar fricative. Although these phones have not previously been recognized as occurring in European Portuguese, they occurred in 115 words out of a corpus of 1304 words, out of which 107 words could be analysed, in recordings made by four native speakers (two men, two women). Time- and frequency-averaged power spectral characteristics are presented, together with a detailed temporal analysis. The frequencies of high-amplitude peaks in the [χ] and [ʁ] spectra clearly indicate a back place of articulation, with median duration across subjects and words of 69 ms and 35 ms. The short (approximately 20 ms), noisy acoustic signal in [ɾ̥] suggests a stop-like manner of articulation, but the turbulence noise characteristics, similar to fricatives, differ from the transient burst noise of plosives.

1 Introduction

We have described elsewhere (Jesus 2001, Jesus & Shadle 2002) our study of Portuguese fricatives, for which we recorded an extensive corpus spoken by four native subjects. In addition to nonsense words, the corpus included fricative-rich real words in sentences. In this paper we discuss fricatives that occurred not by design, that is, fricatives in the positions within the real words that were phonologically rhotics. These were analysed and appear to be the phones [ʁ], [χ] and [ɾ̥] (respectively, unvoiced and voiced uvular fricative, and voiceless tapped alveolar fricative). To date, Portuguese uvular fricatives have been mentioned only as regional phonemic variants in Portugal (Mateus & Andrade 2000) and Brazil (Callou et al. 1994, 1995; Brandão 1995), and there have been no reports of voiceless tapped alveolar fricatives in European Portuguese.

The voiced uvular fricative [ʁ] has been referred to by Mateus & Andrade (2000) as forming part of the phonetic repertoire of European Portuguese, manifested in a rhotic phonological role (of the uvular trill /ʀ/). The voiceless uvular fricative [χ] is mentioned by Callou et al. (1994, 1995), Brandão (1995) and Mateus & Andrade (2000) as a phone in Brazilian Portuguese. Ladefoged & Maddieson (1996: 166–167) reported uvular fricatives in a number of different languages (though not including Portuguese), and assumed these were produced with a vocal tract shape similar to that of uvular stops. For an extensive articulatory study of pharyngeal consonants see the work of Esling (1996).

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To our knowledge, there is no explicit reference to the voiceless tapped alveolar fricative [ɾ̥] in any study of European Portuguese. However, Andrade (1994: 334) does mention that her four speakers 'devoiced' the second rhotic in the word 'apertará' /ɐpɨɾtɐˈɾa/. Voiceless tapped alveolar fricatives are described by Laver (1994: 263) as follows:

> A tapped fricative is made by a swift movement of the active articulator towards the passive articulator, but where the maximum degree of stricture reached is that of close approximation rather than complete closure.

This constriction of the vocal tract lasts for a very short time and results in a low amplitude burst of frication noise. Laver (1994) mentions a Nigerian language, Etsako, that uses a tense voiceless tapped alveolar fricative. Ladefoged & Maddieson (1996: 232–236) also reported several examples of 'fricative and approximant /r/'s' in various world languages (e.g. English, French, Czech and Edo). They observed that for this group of rhotics, in which there is no linguo-palatal contact, 'the typical production is accompanied by friction, in others an approximant is produced'.

Solé (2002) analysed the variation, impairment and extinction of voiced and voiceless trills as a function of intraoral pressure and airflow. The corpora consisted of sustained voiced and voiceless [r], and voiced and voiceless [r] in nonsense words [aˈra] and [iˈri], produced by a male American English speaker and a female Catalan speaker. Voiceless trills exhibited a significantly higher flowrate through the lingual constriction than voiced trills, and trills in [i] context had a higher flowrate than those in [a] context. This tended to result in the generation of friction noise across the lingual constriction for voiceless trills in [i] context. Results of venting the oropharyngeal cavity with catheters of different cross-sectional areas showed that when the oropharyngeal pressure dropped below a certain threshold (a pressure drop of 2.5–3.5 cm H_2O for voiced trills and 5 cm H_2O for voiceless trills) trilling ceased, resulting in a fricative or approximant. A minimum pressure drop across the oral constriction of 4 cm H_2O and a minimum volume velocity of 200 cm^3/s were needed to sustain trilling. Solé also reported that voiceless trills were acoustically and perceptually 'close to fricatives', and proposed 'the reinterpretation of fricative variants of trills as the manifestation of phonological fricatives' (Solé 2002: 683–684).

Extensive studies of rhotics (Wilson 1992, Alwan et al. 1997, Wilson et al. 2000, Catford 2001) described in great detail these phonemes, but there have been no reports of voiceless tapped alveolar fricatives in European Portuguese. It is, however, known that uvular fricatives exist in Portuguese.

Other researchers have studied the acoustic spectra of fricatives in various languages. Here we review their conclusions for uvular and velar fricatives.

Jassem (1967) reported spectral peaks for Polish /x/ at 0.5 kHz, 1.4 kHz and 2.1 kHz, and for /χ/ at 0.6 kHz, 1.1 kHz, 2.3 kHz and 3.4 kHz. Manrique & Massone's (1981) analysis of Argentine Spanish fricatives, in different vowel contexts, revealed a spectral peak in the range 0.9–3 kHz and a lower amplitude spectral peak around 4 kHz for /x/. Nartey (1982) studied fricatives of twelve different languages, reporting the spectral peaks shown in table 1 for /x/ and /χ/ in three different nonsense word vowel contexts /ɪ, a, u/.

Alwan's (1986) results from acoustic vocal tract models showed that for uvular fricatives /χ, ʁ/ formant F1 should be a Helmholtz resonance, F2 and F4 front-cavity resonances and F3 a back-cavity resonance. These predictions were confirmed by spectral analysis results of Arabic consonants which revealed the peaks shown in table 2. The waveform envelope of /ʁ/ was lower in amplitude than that of the surrounding vowels and the formants above F1 were very weak.

Beautemps et al. (1993, 1995) reported spectral peaks for a French speaker uttering /x/ at 600 Hz, 1211 Hz, 2180 Hz and 3665 Hz. Shadle et al. (1995) also presented results of a spectral analysis of /x/ produced by two native German speakers in two environments: sustained, and inserted into nonsense words. The unvoiced velar fricative /x/ had evenly spaced peaks from 1 kHz to 1.5 kHz, peaks at 2 kHz and 3.8 kHz, and a trough around 3 kHz. Vowel context affected the frequencies of spectral peaks of fricatives in nonsense words for

Table 1 Fricative peak frequencies in kHz. For a given place of articulation the same number of rows is used, and if a peak is present its frequency range is given. After Nartey (1982).

	/ixi/	/axa/	/uxu/
Arabic	–	0.5–0.6	0.5–0.6
	1.7–2.3	1.1–1.3	–
	–	3.7–4.4	3.7–4.4
	6.7–7.7	–	–
Navajo	–	–	–
	–	1.1–1.3	–
	3.2–3.7	3.7–4.4	–
	–	–	–
Polish	–	0.2–0.3	0.4–0.5
	2.3–2.7	1.5–1.7	0.8–0.9
	–	–	–
	–	–	–
	/iχi/	/aχa/	/uχu/
Hebrew	–	–	–
	1.5–1.7	1.1–1.3	0.9–1.1
	3.2–3.7	3.2–3.7	3.2–3.7
	–	–	–

Table 2 Arabic fricatives peak frequencies in kHz. The values are averaged across four speakers. After Alwan (1986).

/χiː/	/χaː/	/χuː/
0.4	0.6	0.4
1.6	1.3	0.9
2.6	2.5	2.6
/ʁiː/	/ʁaː/	/ʁuː/
0.4	0.5	0.4
1.4	1.2	0.7
2.5	2.6	2.6

both speakers, but there was more variation in the spectral shape at frequencies above 5 kHz. Place of articulation moved anteriorly in [i] context and rounding in [u] contexts decreased formant frequencies and bandwidths.

2 Recording method

The subjects used in this study were two male (LMTJ and CFGA) and two female (ACC and ISSS) adult Portuguese native speakers, with no reported history of hearing or speech disorders. Subject LMTJ, age 26, is from the city of Aveiro (in the centre of Portugal), and CFGA, age 26, is from Braga (in north Portugal). Speaker ACC, age 33, is from Sintra (a city very close to Lisbon), and ISSS, age 21, is from Lisbon. Some linguists consider all four subjects to speak different dialects; others would consider ACC and ISSS to have the same dialect. At the time of the recordings all subjects had been studying in England for a period of two to three years.

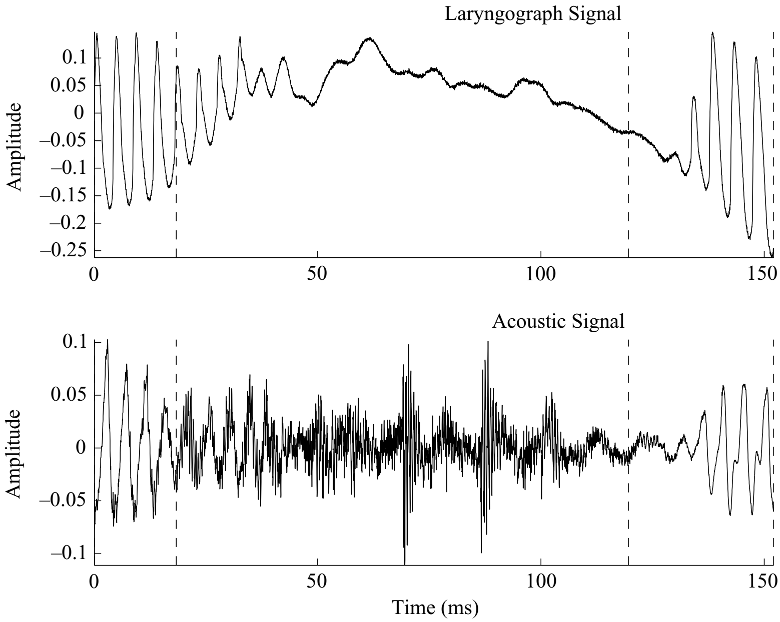

Figure 1 Laryngograph and acoustic signal of fricative [χ] and adjacent vowels in *diga relevo* [ˈdigɐ χɨˈlev]. Time = 0 marks the start of the vowel to fricative transition; dashed lines mark the start and end of the fricative, and the end of fricative to vowel transition. Corpus 3 (Speaker ISSS).

Recordings were made in a sound-treated room using a Bruel & Kjaer 4165 1/2 inch microphone located 1 m in front of the subject's mouth, connected to a Bruel & Kjaer 2639 preamplifier. The signal was bandpass-filtered from 22 Hz to 22 kHz, and amplified, by a Bruel & Kjaer 2636 measurement amplifier. A laryngograph signal (Lx) was also collected using a laryngograph processor.[1] The acoustic speech signal and Lx were recorded with a Sony TCD-D7 DAT system at 16 bits, with a sampling frequency of 48 kHz, and digitally transferred to a computer for post-processing.

A rich variety of phonetic contexts using both real Portuguese words and nonsense words was selected to study the most relevant phoneme variants, and describe fully the spectral and articulatory characteristics of Portuguese fricative consonants. The corpora included sustained fricatives (Corpus 1a and 1b) and a set of nonsense words (Corpus 2). Corpus 3 consisted of 154 words, each said within the frame sentence *Diga . . . , por favor* /ˈdigɐ . . . puɾ ˈfɐvoɾ/, which was used to record the words in the corpus in a balanced phonetic context and with a neutral prosody. To study the effects of coarticulation in connected speech, we devised a set of sentences (Corpus 4) with words selected from Corpus 3. The complete listings of the corpora were presented in Jesus & Shadle (2002); the words considered here are tabulated in the appendix (in tables A1–A6).

3 Analysis method

During the annotation phase, we noticed that 115 words contained a second fricative, besides the one initially selected for analysis. These included 21 examples of [χ], similar to that shown in figure 1, and two of its voiced counterpart, [ʁ]. Eight of the /ɾ, ʀ/ phonemes in Corpus 3

[1] Model LxProc, type PCLX produced by Laryngograph Ltd, UK.

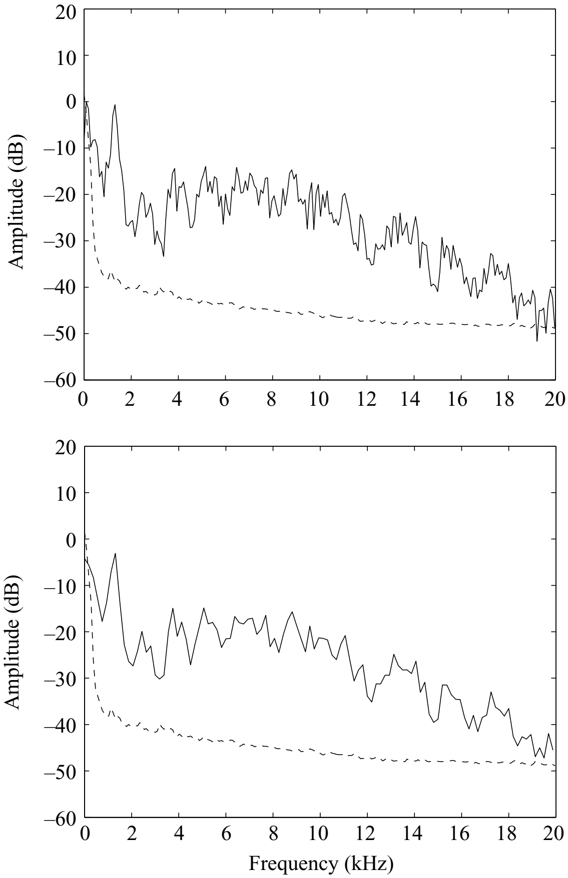

Figure 2 Time-averaged (top) and time and frequency-averaged (bottom) spectra of fricative [χ] in *diga ressaca* ['digɐ χ'sakɐ]. The dashed curve is the time-averaged spectrum of the room noise. Corpus 4 (Speaker CFGA).

and 4 seemed to have been realized as fricatives, but are not included in tables A1–A6 or used for analysis. This is because the fricatives were part of a consonant cluster where it was impossible to determine precise boundaries for each phoneme.

Words containing /ʀ, ɾ/ that were realized as fricatives were analysed. Time waveforms, such as the one shown in figure 1, of words containing [χ], [ʁ] and [ɾ̥] were manually analysed to detect the start of the vowel-fricative (VF) transition, the start and end of the fricative, and the start of the fricative-vowel (FV) transition. During the VF transition, there is a decrease in amplitude, voicing ceases (for unvoiced fricatives) and frication noise starts. During the FV transition, there is an increase in amplitude, voicing starts (for unvoiced fricatives) and frication noise ceases. These events do not occur simultaneously or always in the same order, making the segmentation a somewhat subjective process. However, it is important to segment consistently, because the results of the analysis methods depend on where the boundaries are placed. The amplitude and voicing changes appear in both acoustic and Lx signals, which aids the segmentation process. The laryngograph signal was also used in the decision process to determine the VF and FV boundaries. For unreduced vowels there was always significant voicing, and for the duration of most fricatives the laryngograph signal changed drastically. Therefore, the amplitude of the laryngograph signal was an important cue in determining the boundaries between the different phones. When it was not clear from the acoustic signal where

Table 3 Fricative peak frequencies in kHz. The values in brackets are the median of the frequency range.

	[ɾ̥]	
LMTJ	1.4–1.8 (1.5) 2.1–3.0 (2.3) –	
CFGA	1.3–1.4 2.1–2.8 –	
ACC	1.3–2.3 (1.6) 1.8–3.5 (2.8) 8.9	
ISSS	1.6–2.0 (1.8) 2.7–3.7 (3.2) 12.3–14.0 (12.8)	
	[χ]	[ʁ]
LMTJ		
CFGA	1.0–1.4 (1.2) 2.2–2.8 (2.4) 3.3–3.9 (3.9) 8.5–9.1 (8.8)	1.1 2.3 3.4 9.5
ACC	1.3 2.1 3.2 –	1.6 2.6 3.4 10.2
ISSS	1.1–1.6 (1.5) – 3.3–4.0 (3.7) –	– – – –

the fricative started and ended (especially for voiced fricatives), the laryngograph signal was used as an additional cue, because its amplitude diminishes during the VF transition and increases during the FV transition.

For example, as can be seen in figure 1, the start of the VF transition was chosen because both signals begin to decrease in amplitude noticeably at that point. The start of the fricative is placed where the noise in the acoustic signal becomes more apparent, even though voicing has not yet ceased; the end of the fricative is placed where the frication noise ceases to be visible in the acoustic signal, and where voicing begins again in the Lx signal. Segmenting the 'steady-state' part of the fricative in this way places more weight on the presence of significant noise than on the presence or absence of voicing. It thereby makes available for spectral analysis the entire region in which noise production seems to be relatively steady, thus aiding identification of place cues.

Following segmentation, the duration of fricatives, VF transitions and FV transitions were then registered, and spectral analysis was carried out. Since some of the fricatives were very short (durations ranged from 11 ms to 117 ms), the necessary spectral averaging was achieved by first time-averaging and then spectral smoothing. Time-averaged spectra such as the one shown in figure 2 (top), computed using three 11 ms windows (one left-aligned to the start of the fricative, one right-aligned to the end of the fricative and one centred at the middle of the fricative), were smoothed in the frequency domain (according to Bendat & Piersol

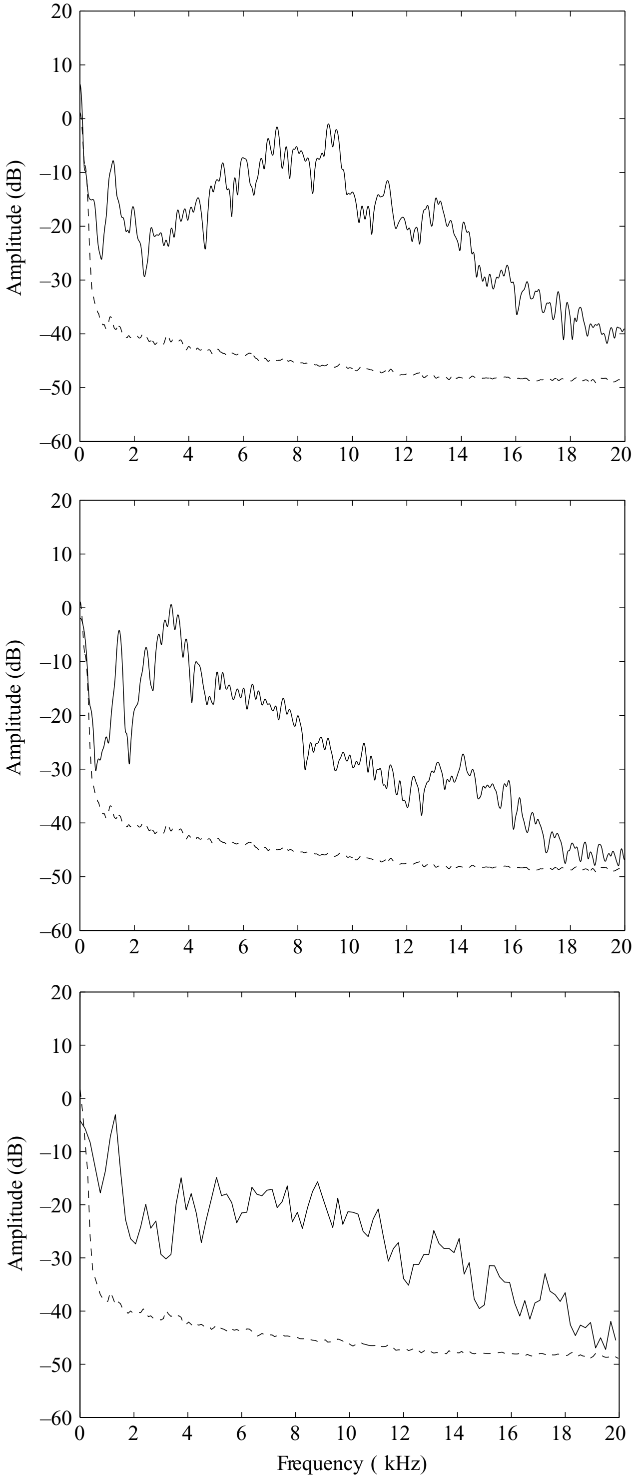

Figure 3 Averaged power spectra of [s] (top) in *ressaca* [ɐ χ'sakɐ] (preceded by the word *diga* ['digɐ]), [ʃ] (middle) in *meche* ['mɛʃɨ], and [χ] (bottom) in *ressaca* [ɐ χ'sakɐ]. The dashed curve is the time-averaged spectrum of the room noise. Corpus 4 (Speaker CFGA).

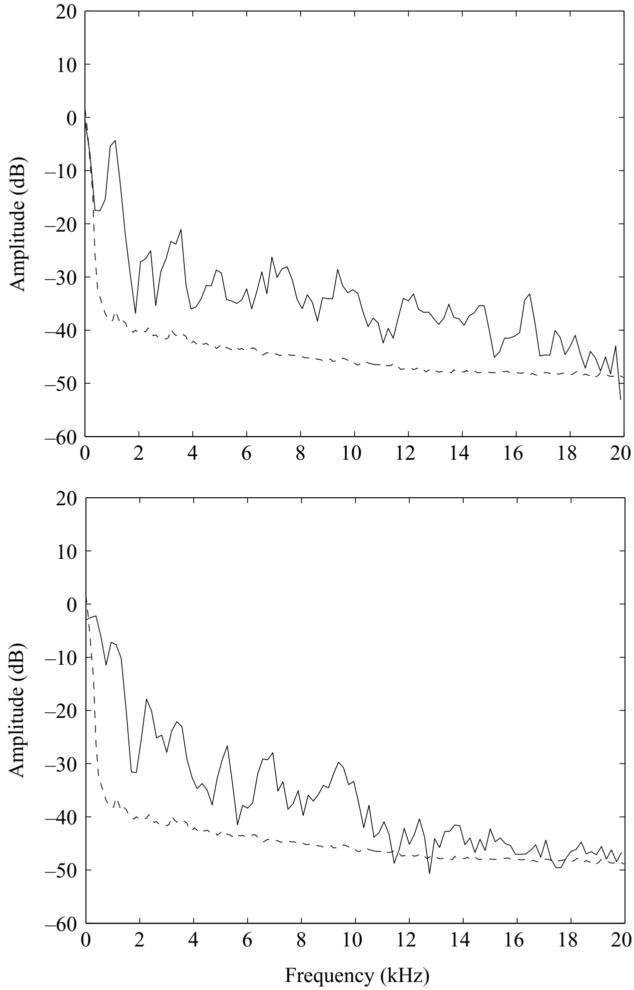

Figure 4 Time- and frequency-averaged spectra of fricative [χ] (top) in *rosa* [ɐ'χɔzɐ] and [ʁ] (bottom) in *rosa* [ɐ'ʁɔzɐ] (both preceded by the word *diga* ['digɐ]). The dashed curve is the time-averaged spectrum of the room noise. Corpus 4 (Speaker CFGA).

2000: 432–434) by averaging together the results of two contiguous spectral components (see figure 2, bottom).

4 Results

4.1 Spectral analysis

Fricative spectra can be modelled as the result of exciting a pole-zero transfer function with noise. Spectral peaks thus do not necessarily indicate a resonance, and resonances that are nearly cancelled may not produce strong spectral peaks. However, as shown in figure 3, the place of a fricative is represented in general by the overall spectral shape. On top, [s], with

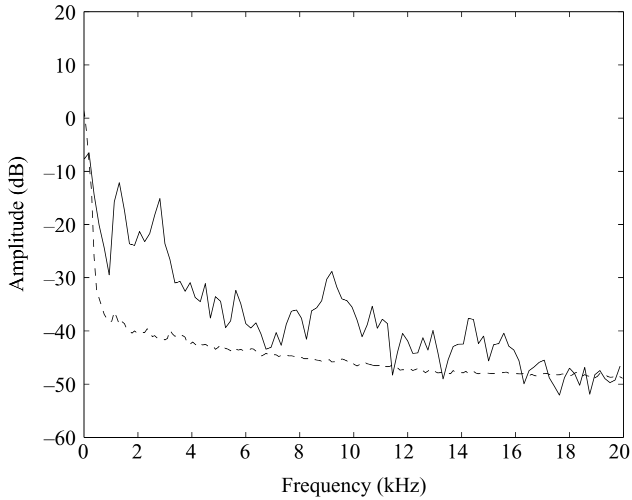

Figure 5 Time- and frequency-averaged spectra of fricative [ɾ̥] in *ver* [veɾ̥ u] (followed by the word *o* [u]). The dashed curve is the time-averaged spectrum of the room noise. Corpus 4 (Speaker CFGA). Same token is used as in figure 9.

the shortest front cavity, has a broad peak at approximately 8 kHz; [ʃ], centre, has a peak at approximately 3.5 kHz; and /r/, realized – as we believe – as [χ] (bottom), a series of peaks at 1.3 kHz, 2.4 kHz, indicating a still longer front cavity. Across all tokens of [χ], peaks occur in the range of 1.0–1.6 kHz, 2.1–2.8 kHz and 3.2–4 kHz, consistent with other authors' descriptions of uvular fricatives. As listed in table 3, for all subjects and all corpora, a trough was always present in the range 1.8–2.5 kHz; sometimes a low amplitude broad peak was also visible, centered in the range 8.5 kHz to 9.1 kHz. There is a 30–40 dB falloff of amplitude over the 1.5–20 kHz frequency range. A spectrogram of a word with the fricative [χ] is given in figure 7.

In our limited inventory there are only two occurrences of fricative [ʁ], as shown in table A2, with spectral characteristics very similar to its unvoiced counterpart, as listed in table 3 and shown in figure 4. A spectrogram of a word with the fricative [ʁ] is given in figure 8.

The spectral results for [ʀ, ʁ] for these Portuguese subjects are comparable to those of velar and uvular fricatives in various other languages reviewed in the introduction.

The spectrum of fricative [ɾ̥] has peaks in the ranges listed in table 3, including a low amplitude broad peak that can be centred from 8.9 kHz to 14 kHz; it also usually has a trough around 0.8–1.5 kHz for all subjects and all corpora. However, these cues in the spectra are not always visible and there is great variability in the spectral structure (but not the overall amplitude). There is a 30–40 dB falloff of amplitude over the 2–20 kHz frequency range. A time- and frequency-averaged spectra of two examples of fricative [ɾ̥] are given in figures 5 and 6, and spectrograms of words with the fricative [ɾ̥] are given in figures 9 and 10.

There is relatively little acoustic description of [ɾ̥] in the literature, and given the spectral variation in our tokens and their low amplitude it is harder to make a strong case for the alveolar place in the absence of any articulatory data. For the sounds that are phonologically /ɾ/, the voiced tapped alveolar rhotic, it seems justified to classify voiceless tokens with fricative-like noise as [ɾ̥]. However, some sounds that are phonologically the uvular trill /ʀ/ were also realized with phones that we have classified as [ɾ̥]. We will consider these cases again after we have presented the results of the temporal analysis.

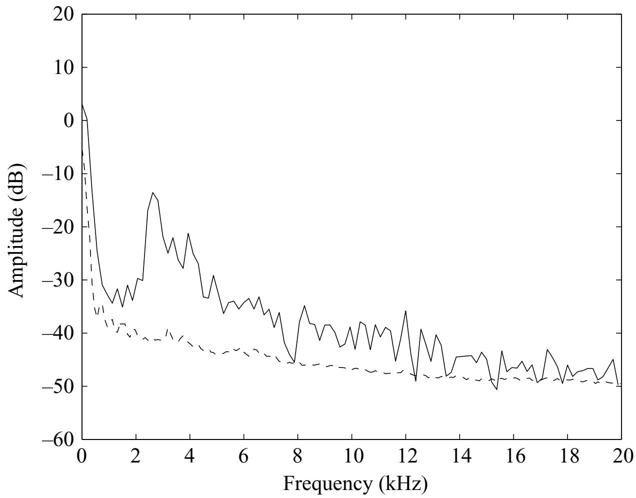

Figure 6 Time- and frequency-averaged spectra of fricative [ɾ̥] in *girar* [ʒiˈɾ̥ɐɾ]. The dashed curve is the time-averaged spectrum of the room noise. Corpus 3 (Speaker LMTJ). Same token is used as in figure 10.

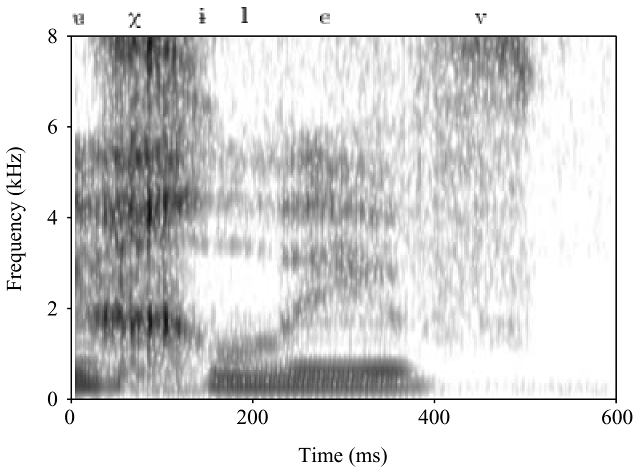

Figure 7 Spectrogram of the word *relevo* [ɐ χɨˈlev] (preceded by the word *diga* [ˈdigɐ]). Corpus 3 (Speaker ISSS).

4.2 Temporal analysis

In table 4, we show the number of tokens of /ɾ, ʀ/ that were realized as [ɾ, ɾ̥, ʁ, χ, ʀ] by subject and corpus. From table 4, it is clear that most of the sound changes are from /ɾ/ → [ɾ̥], observed mainly for LMTJ, ACC and ISSS; of these, most occurrences are syllable-final, as shown in table 5. Another change is from /ʀ/ → [χ], observed mainly for CFGA and ISSS; of these, most occur syllable-initially. Table 6 shows the breakdown in terms of the occurrence in stressed syllables (and whether onset or coda) and unstressed syllables. The way in which these results differ by subject cannot be explained by dialect, since ACC and ISSS are the only subjects with the same dialect but have different patterns of phonetic realization.

Durations of the steady-state portion of the fricatives and of their VF and FV transitions were measured to describe the characteristics of European Portuguese and to compare them

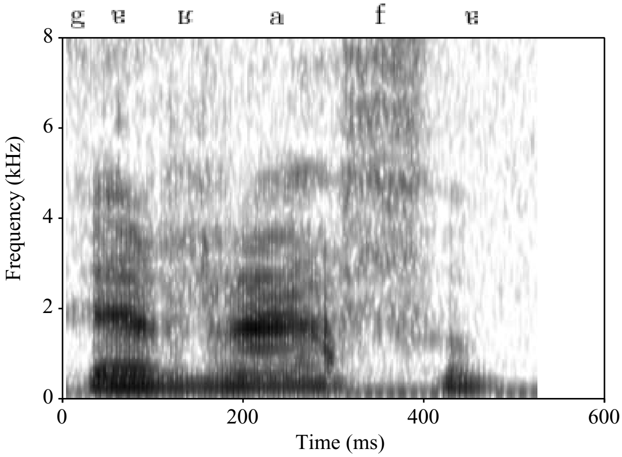

Figure 8 Spectrogram of the word *garrafa* [gɐˈʁafɐ]. Corpus 3 (Speaker ACC).

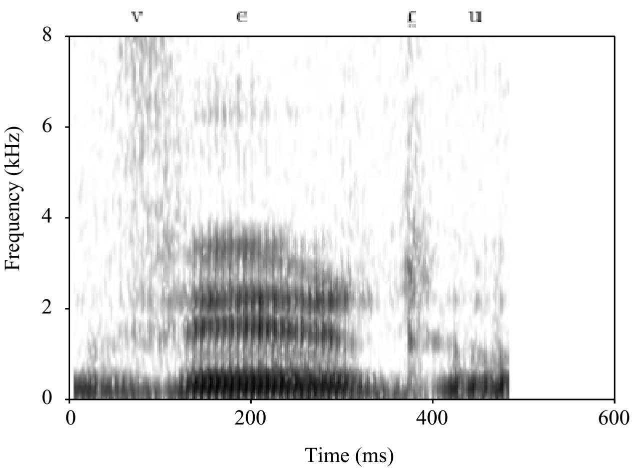

Figure 9 Spectrogram of the word *ver* [veɾ̥ u] (followed by the word *o* [u]). Corpus 4 (Speaker CFGA).

with results reported for various other languages. The duration of fricative [χ] varied from 23 ms to 117 ms (median duration = 69 ms), the VF transition from 15 ms to 41 ms (median duration = 25 ms), and the FV transition from 22 ms to 43 ms (median duration = 32 ms); durations for specific examples are shown in table A1 in the appendix. The duration of fricative [ɾ̥] varies from 11 ms to 85 ms (median duration = 22 ms), the VF transition from 12 ms to 103 ms (median duration = 30 ms) and the FV transition from 13 ms to 58 ms (median duration = 21 ms), as shown in tables A3–A6.

These durational results for Portuguese uvular fricatives are different from those of Manrique & Massone's (1981) study of Argentine Spanish, who showed that for velar fricatives the average durations for four speakers were: /x/ (unstressed, stressed) – 196 ms, 147 ms; /ɣ/ (unstressed, stressed) – 92 ms, 58 ms. Results of a study by Alwan (1986), of the production and perception of Arabic pharyngeal and uvular consonants, revealed fricative duration values similar to those of Manrique & Massone (1981). The voiceless consonants were longer (/χ/ – 169 ms averaged across all vowel contexts and four speakers) than the voiced consonants

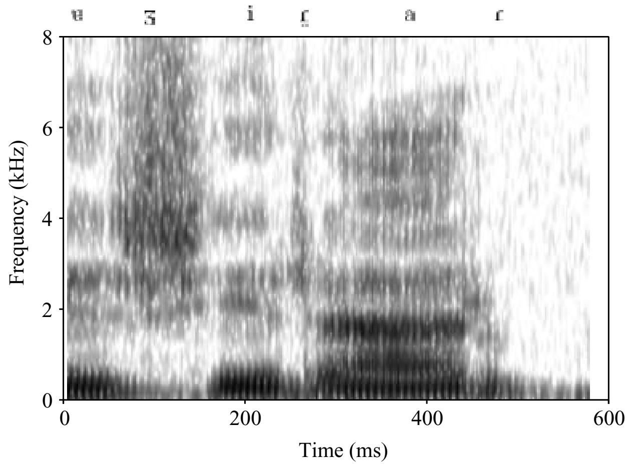

Figure 10 Spectrogram of the word *girar* [ɐ ʒiˈɾ̥aɾ] (preceded by the word *diga* [ˈdigɐ]). Corpus 3 (Speaker LMTJ).

Table 4 Number of occurrences of phones [ʀ], [χ], [ʁ], [ɾ] and [ɾ̥], and their particular phonological roles.

Speaker	Corpus	Phonological Role	Phonetic Realization					Total
			[ʀ]	[χ]	[ʁ]	[ɾ]	[ɾ̥]	
LMTJ	3	/ɾ/	0	0	0	24	26	50
LMTJ	4	/ɾ/	0	0	0	29	9	38
LMTJ	3	/ʀ/	4	0	0	0	2	6
LMTJ	4	/ʀ/	0	0	0	0	4	4
CFGA	3	/ɾ/	0	0	0	51	0	51
CFGA	4	/ɾ/	0	0	0	61	2	63
CFGA	3	/ʀ/	1	5	0	0	0	6
CFGA	4	/ʀ/	0	5	1	0	0	6
ACC	3	/ɾ/	0	0	0	30	22	52
ACC	4	/ɾ/	0	0	0	51	9	60
ACC	3	/ʀ/	1	1	1	0	2	5
ACC	4	/ʀ/	0	0	0	3	3	6
ISSS	3	/ɾ/	0	0	0	42	8	50
ISSS	4	/ɾ/	0	0	0	37	6	43
ISSS	3	/ʀ/	0	6	0	0	0	6
ISSS	4	/ʀ/	0	4	0	0	0	4
Total			6	21	2	328	93	450

(/ʁ/ – 113 ms), but vowel context did not significantly affect the duration of the consonants. The European Portuguese fricatives studied here may possibly be shorter as a result of the naturalness of the corpora studied here (only real words), contrary to the focus on nonsense words in the studies of Manrique & Massone (1981) and Alwan (1986).

The median duration of [ɾ̥] was 22 ms, very similar to the closure duration of 20–30 ms for alveolar taps reported by Recasens (1991) for one Catalan speaker (the author), who also mentions that, for some vowel contexts, there is an incomplete closure at the central alveolar

Table 5 Number of occurrences of phones [χ], [ʁ], and [ɾ̥], in word-initial, word-medial, word-final and syllable-final positions. For word-medial and word-final columns, the numbers shown are *X*(*Y*), where X = total number in word-medial(final) position, and Y = number in word-medial(final) and syllable-final position.

	Word-Initial	Word-Medial	Word-Final	Total Syllable-Final
[χ]	15	4 (0)	2 (0)	0
[ʁ]	1	1 (0)	0 (0)	0
[ɾ̥]	10	30 (8)	53 (53)	61

Table 6 Number of occurrences of phones [χ], [ʁ], and [ɾ̥], at the onset and coda of stressed syllables, and in unstressed syllables.

	Stressed (Onset)	Stressed (Coda)	Unstressed
[χ]	10	2	9
[ʁ]	2	0	0
[ɾ̥]	12	54	27

area. This probably means that some of his data included voiceless tapped alveolar fricatives (the author does not discuss in much detail the characteristics of the acoustic signal, and mostly shows electropalatography analysis results). Monnot & Freeman (1972) also reported, in an earlier study of American English and Spanish speakers, durations of 30–40 ms for taps. The overall amplitude of [ɾ̥] was quite low, which perhaps suggests a different classification of this speech sound, as an allophone of both /t/ and /d/, as previously suggested by Kent & Read (1992: 141–142) for [ɾ]. The short duration of [ɾ̥] suggests a stop-like manner of articulation, but it has fricative turbulence noise characteristics, different from the transient burst noise of plosives.

5 Conclusion

In this acoustic phonetic study of European Portuguese fricatives, the phones [ɾ̥], [ʁ] and [χ] were found to occur naturally and quite regularly, contrary to what had been previously reported in phonological studies of this language. The phoneme /ɾ/ is most likely to be realized as [ɾ̥] in word-final position; effects of stress and position in the syllable were investigated but proved inconclusive with the corpora being used. The uvular fricative [χ] seems to be produced on a regular basis only by speakers CFGA and ISSS, which is probably related to their particular production strategies, and its voiced counterpart [ʁ] is used very seldom. The corpora we had available allow us to propose [χ] as a phone of standard European Portuguese, but more data are needed to confirm this hypothesis. The frequency ranges of [χ] peaks (1.0–1.6 kHz, 2.1–2.8 kHz and 3.2–4 kHz) clearly indicate a back place of articulation, with median duration of 69 ms. [ɾ̥] seems to be quite common in European Portuguese, and definitely should be considered in future fricative and plosive studies of this language.

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Appendix

This appendix lists the results of the time analysis of Corpus 3 and 4 uvular fricatives and voiceless tapped alveolar fricatives, and their VF (vowel–fricative) and FV (fricative–vowel) transitions. A broad phonetic transcription is also included. The data presented include: the VF transition duration, the fricative duration F, and the FV transition duration.

The file numbering of words from Corpus 4 has two parts: a number that refers to the sentence where the words occur and a word number which is the same as that used in Corpus 3.

Coarticulation across word boundary is indicated in the phonetic transcription of words with fricatives at the beginning or end by an additional initial or final phoneme, separated from the transcription of the word we are analysing by a white space. For example, the

Table A1 Occurrences of voiceless uvular fricative /χ/, and for each occurrence, durations of transition (VF and FV) and steady-state (F) regions.

Speaker	Corpus	File N.	Example	IPA	VF (ms)	F (ms)	FV (ms)
CFGA	3	94	relevo	[ɐ χɨˈlev]	27	82	43
CFGA	3	82	ressaca	[ɐ χˈsakɐ]	15	84	–
CFGA	4	7–82	ressaca	[ɐ χˈsakɐ]	28	55	–
CFGA	4	7r1–82	ressaca	[ɐ χˈsakɐ]	41	102	–
CFGA	4	7r2–82	ressaca	[ɐ χˈsakɐ]	25	75	–
CFGA	3	14	rosa	[ɐ ˈχɔzɐ]	36	55	33
CFGA	4	4–14	rosa	[ɐ ˈχɔzɐ]	25	69	40
CFGA	4	4r2–14	rosa	[ɐ ˈχɔzɐ]	24	54	33
CFGA	3	71	garrafa	[gɐˈχafɐ]	18	64	24
CFGA	3	16	zurrar	[zuˈχar]	38	47	36
ACC	3	4	ferro	[ɐ ˈfɛχ]	17	23	–
ISSS	3	94	relevo	[ɐ χɨˈlev]	19	102	33
ISSS	3	82	ressaca	[ɐ χˈsakɐ]	18	66	–
ISSS	4	7–82	ressaca	[ɐ χˈsakɐ]	25	68	–
ISSS	4	7r–82	ressaca	[ɐ χˈsakɐ]	25	55	–
ISSS	3	14	rosa	[ɐ ˈχɔzɐ]	20	100	25
ISSS	4	4–14	rosa	[ɐ ˈχɔzɐ]	26	106	25
ISSS	4	4r–14	rosa	[ɐ ˈχɔzɐ]	23	61	31
ISSS	3	71	garrafa	[gɐˈχafɐ]	30	72	22
ISSS	3	16	zurrar	[zuˈχaɾ]	21	117	31
ISSS	3	4	ferro	[ˈfɛχ]	23	100	–

Table A2 Occurrences of voiced uvular fricative /ʁ/, and for each occurrence, durations of transition (VF and FV) and steady-state (F) regions.

Speaker	Corpus	File N.	Example	IPA	VF (ms)	F (ms)	FV (ms)
CFGA	4	4r1–14	rosa	[ɐ ˈʁɔzɐ]	28	28	63
ACC	3	71	garrafa	[gɐˈʁafɐ]	32	42	39

Table A3 Occurrences of voiceless tapped alveolar fricative /ɾ̥/ (Speaker LMTJ), and for each occurrence, durations of transition (VF and FV) and steady-state (F) regions.

Corpus	File N.	Example	IPA	VF (ms)	F (ms)	FV (ms)
4	7–82	ressaca	[ɾ̥ɨˈsakɐ]	–	12	13
3	14	rosa	[ɨ͜ˈɾ̥ɔzɐ]	–	15	39
4	4–14	rosa	[a ˈɾ̥ɔzɐ]	34	43	19
4	4–14r	rosa	[a ˈɾ̥ɔzɐ]	35	52	16
4	7–82r	ressaca	[ɾ̥ˈsakɐ]	–	28	–
3	48	girar	[ʒiˈɾ̥aɾ]	33	23	38
3	18	ferir	[fiˈɾ̥iɾ]	36	15	21
3	86–1r	vermelho	[vɨɾ̥ˈmɐʎ]	41	21	–
3	86–2r	vermelho	[viɾ̥ˈmɐʎ]	32	24	–
3	99	Zaire	[ˈzajɾ̥ɨ]	32	22	16
3	46	arejar	[ɐɾ̥ɨˈʒa]	43	16	14
4	5–46r	arejar	[ɐɾ̥͜ɨˈʒaɾ]	33	27	–
3	71	garrafa	[gɐˈɾ̥afɐ]	34	12	58
4	3–113	zarpar	[zɐɾ̥͜ɾˈpaɾ]	25	23	–
4	3–113r	zarpar	[zɐɾ̥͜ɾˈpaɾ]	17	27	–
3	8	amoroso	[ɐmuˈɾ̥oz]	31	27	30
3	78	chorar	[ʃuˈɾ̥aɾ]	40	20	39
3	47	falir	[fɐˈliɾ̥]	29	18	–
3	139	subir	[suˈbiɾ̥]	33	32	–
4	3–139r	subir	[suˈbiɾ̥]	40	42	–
3	122	viver	[viˈveɾ̥]	32	17	–
3	102	ver	[veɾ̥͜ɨ]	24	23	–
4	12–102r	ver	[veɾ̥ u]	30	24	19
3	22	dever	[diˈveɾ̥͜ɨ]	32	20	–
3	57	mover	[muˈveɾ̥͜ɨ]	16	19	–
3	39	saber	[sɐˈbeɾ̥]	29	25	–
3	98	efectuar	[iˈfɛtwaɾ̥]	37	12	–
3	7	vogar	[ɐ ˈvugaɾ̥]	21	21	–
3	137	assar	[ɐˈsaɾ̥͜ɨ]	28	21	–
4	12–137r	assar	[ɐˈsaɾ̥]	103	36	–
3	113	zarpar	[zɐɾˈpaɾ̥͜ɨ]	24	37	–
3	16	zurrar	[zuˈRaɾ̥]	24	20	–
3	97	azar	[ɐˈzaɾ̥͜ɨ]	34	16	–
3	146	acusar	[ɐkuˈaɾ̥]	30	24	–
3	65	chegar	[ʃɨˈgaɾ̥]	21	20	–
3	28	chamar	[ʃɐˈmaɾ̥͜ɨ]	22	24	–
3	114	achar	[ɐˈʃaɾ̥]	25	18	–

Table A4 Occurrences of voiceless tapped alveolar fricative /ɾ̥/ (Speaker ACC), and for each occurrence, durations of transition (VF and FV) and steady-state (F) regions.

Corpus	File N.	Example	IPA	VF (ms)	F (ms)	FV (ms)
3	14	rosa	[ˈɾ̥ɔzɐ]	–	34	40
3	82	ressaca	[ɾ̥ˈsakɐ]	–	16	–
3	10	Zópiro	[ˈzɔpiɾ̥u]	36	23	19
3	72	germe	[ˈʒɛɾ̥m]	34	18	–
4	3r1–113	zarpar	[zɐɾ̥ˈpaɾ]	32	22	–
4	3r2–113	zarpar	[zɐɾ̥ˈpaɾ]	22	21	–
3	16	zurrar	[zuˈɾ̥a**ɾ̥**ɨ]	21	31	34
3	16	zurrar	[zuˈ**ɾ̥**aɾ̥ɨ]	27	13	26
4	9r1–44	furar	[fuˈɾ̥aɾ]	35	11	13
4	10r1–58	Brasil	[bɾ̥ɐˈzil]	–	15	19
3	99	Zaire	[ˈzajɾ̥ɨ̮]	30	19	–
3	18	ferir	[fɨˈɾiɾ̥]	23	28	–
3	47	falir	[fɐˈliɾ̥]	44	15	–
3	139	subir	[suˈbiɾ̥]	30	24	–
3	108	agir	[ɐˈʒiɾ̥]	30	20	–
3	122	viver	[viˈveɾ̥]	14	33	–
3	102	ver	[veɾ̥]	30	23	–
4	12r1–102	ver	[veɾ̥]	51	24	–
3	22	dever	[dɨˈveɾ̥]	27	17	–
4	12r1–22	dever	[dɨˈveɾ̥ɨ̮]	26	18	–
3	131	aquecer	[ɐkɛˈseɾ̥]	40	25	–
3	98	efectuar	[iˈfɛtwaɾ̥]	24	23	–
3	105	levar	[lɨˈvaɾ̥ɨ̮]	19	14	–
3	137	assar	[ɐˈsaɾ̥]	17	25	–
4	12–137	assar	[ɐˈsaɾ̥]	30	33	–
4	12r2–137	assar	[ɐˈsaɾ̥]	53	16	–
3	126	zelar	[ˈzɨlaɾ̥]	27	20	–
3	97	azar	[ɐˈzaɾ̥]	25	13	–
3	48	girar	[ʒiˈɾaɾ̥ɨ̮]	19	15	–
3	1	originar	[oriʒiˈnaɾ̥ɨ̮]	27	19	–
4	9r2–44	furar	[fuˈɾaɾ̥]	31	15	–
3	120	tugir	[tuˈʒiɾɾ̥̮]	–	15	–

word analysed in *Diga relevo, por favor* [ˈdigɐ χɨˈlev puɾ ˈfɐvoɾ] is listed in the phonetic transcription of table A1 as [ɐ χɨˈlev].

Within each table, the examples are ordered by position in the word, from word-initial to word-medial to word-final. Where more than one subject is included in a table, examples within each subject are ordered by position within the word.

Table A5 Occurrences of voiceless tapped alveolar fricative /ɾ̥/ (Speaker CFGA), and for each occurrence, durations of transition (VF and FV) and steady-state (F) regions.

Corpus	File N.	Example	IPA	VF (ms)	F (ms)	FV (ms)
4	12r2–102	ver	[veɾ̥ u]	65	36	21
4	12r1–137	assar	[ɐˈsaɾ̥]	37	85	–

Table A6 Occurrences of voiceless tapped alveolar fricative /ɾ̥/ (Speaker ISSS), and for each occurrence, durations of transition (VF and FV) and steady-state (F) regions.

Corpus	File N.	Example	IPA	VF (ms)	F (ms)	FV (ms)
3	86	vermelho	[viɾ̥ˈmeʎu]	29	14	–
4	5–46	arejar	[ɐɾ̥ɨˈʒaɾ]	27	12	25
4	5r–46	arejar	[ɐɾ̥ˈʒaɾ]	28	26	–
3	130	mares	[ˈmaɾ̥ʃ]	12	22	–
3	10	Zópiro	[ˈzɔpiɾ̥]	35	24	–
3	99	Zaire	[ˈzajɾ̥]	37	21	–
3	18	ferir	[fɨˈɾiɾ̥]	37	32	–
3	139	subir	[suˈbiɾ̥]	40	22	–
4	3r–139	subir	[suˈbiɾ̥]	40	42	–
3	108	agir	[ɐˈʒiɾ̥]	43	36	–
3	28	chamar	[ʃɐˈmaɾ̥]	29	20	–
4	12–137	assar	[ɐˈsaɾ̥]	27	54	–
4	12r–137	assar	[ɐˈsaɾ̥]	17	66	–
4	11r–114	achar	[ɐˈʃaɾ̥]	46	41	–

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