Phonetic variability of rhotic realization: evidence from Greek voiced /Cr/ clusters

Katerina Nicolaidis[1] & Mary Baltazani[2]
Aristotle University of Thessaloniki[1] & University of Oxford[2]
knicol@enl.auth.gr, mary.baltazani@phon.ox.ac.uk

Abstract

Η μελέτη χρησιμοποιεί ακουστικά και ηλεκτροπαλατογραφικά δεδομένα για να εξετάσει την παραγωγή του ελληνικού /r/ σε συμφωνικά συμπλέγματα /Σr/ με ηχηρά αποφρακτικά /b, d, g, v, ð, ɣ/. Τα αποτελέσματα επιβεβαιώνουν τη σύνθετη παραγωγή του /r/, η οποία περιλαμβάνει ένα φωνηεντικό μέρος και μια σύντομη περίοδο μερικής ή ολικής φραγής, καθώς και ποικιλία στη θέση και στον τρόπο άρθρωσης. Οι διαμορφωτές του φωνηεντικού μέρους έχουν πιο κεντρικές τιμές σε σχέση με το φωνήεν της συλλαβής. Η σύγκριση των αποτελεσμάτων με προηγούμενα δεδομένα σε συμπλέγματα με άηχο αποφρακτικό δείχνουν μεγαλύτερη διάρκεια φραγής και μικρότερη διάρκεια φωνηεντικού μέρους σε περιβάλλον άηχου αποφρακτικού και σε περιβάλλον έκκροτου σε σχέση με τριβόμενο σύμφωνο.

Keywords: rhotic, cluster, obstruent, Greek, acoustic analysis, electropalatography

1 Introduction

Rhotic production can be highly variable across languages, dialects, socioeconomic contexts, genders, age-groups, linguistic contexts, positions in the word or phrase, words with different number of syllables, speaking rates, and speakers (e.g. Ladefoged & Maddieson 1996; Recasens & Espinosa 2007).

Modern Greek rhotic production has been traditionally described as a tap or trill articulation (e.g. Philippaki-Warburton 1992; Arvaniti 1999). Experimental studies have shown that the Greek rhotic typically involves a single constriction of short duration, which indicates tap articulation. Several studies using acoustic and electropalatographic data have, however, documented variability in manner (e.g. tap, trill, approximant production), place (advanced vs. retracted in the alveolar ridge) as a function of context (consonantal and vocalic), position in the word (word-initial as a singleton or part of a cluster, phrase-initial, as a singleton between vowels, syllable-final in a hetero-syllabic rC sequence or word-final as a singleton) and speaker (Baltazani 2009; Baltazani & Nicolaidis 2013a, b; Nicolaidis & Baltazani 2011, 2013, 2014). In addition, several of these studies reported the presence of a vocoid during the production of the rhotic which was evident not only in clusters, as has been found for various other languages (e.g. Recasens & Espinosa 2007; Bradley 2004; Colantoni &Steele 2005; Vago &Gósy 2007; Savu 2012), but also as a singleton in word-initial and word-final position (cf. Recasens & Espinosa 2007; Savu 2012). These studies showed variation in vocoid production influenced by context, position and speaker (cf. Recasens & Espinosa 2007). The vocoid phase was generally longer than the constriction phase and had formant structure that was similar but more centralised than the nuclear vowel (cf. Quillis 1993). Based on these studies, a categorisation of the different types of rhotic realisation with phonetic details of both the constriction and vocoid production (Table 1) was provided in Nicolaidis & Baltazani (2014). We adopt this classification, with some modifications (see section 2), for the analysis in the present paper.

Categories	***Acoustic characteristics***	***Articulatory (EPG) characteristics***
Constriction		
1	Stop-like interval followed by burst.	Complete closure across one or more rows in the alveolar zone.
2a	Stop-like interval without a burst.	Complete closure across one or more rows in the alveolar zone.
2b	Stop-like interval without a burst. Typically more energy during the constriction phase on the acoustic data.	Incomplete closure in the alveolar zone.
3	Presence of high amplitude formant structure during the constriction phase.	Incomplete closure in the alveolar zone. Open linguo-palatal patterns.
4	Noise or breathiness during the constriction phase.	Incomplete closure in the alveolar zone.
5	Multiple constrictions (typically two) indicating trill production.	Typically first contact is more constricted than second. The latter can be very open.
Vocoid		
1v	Modal or breathy quality with presence of formant structure	
2v	Whispered quality	
3v	No vocoid	

Table 1. Categorisation of different types of rhotic realization (from Nicolaidis &Baltazani 2014: 1194-1195).

The present study aims to examine variation in rhotic production in two novel contexts, i.e. /Cr/ clusters with C = voiced stop /b, d, g/ or voiced fricative /v, ð, ɣ/. It complements previous work on Greek rhotic production and aims to address the following questions:

(a) Is the range of variability similar to previously reported variability in different contexts (i.e. types of rhotic articulation, frequency of different productions, constriction vs. vocoid phases, context and speaker variability)?
(b) Are there differences in rhotic production in voiced /Cr/ clusters depending on the manner of the C, i.e. fricative vs. stop?
(c) Are there differences in rhotic production in /Cr/ clusters depending on the voicing of the C? For this analysis, /r/ production in voiced stop contexts is compared to our previously reported data on /r/ in voiceless stop contexts.

Overall, this study aims to contribute to a more comprehensive understanding of the production characteristics of rhotics and the factors that influence rhotic realisation resulting in the rich diversity of rhotic production across languages.

2 Method

Words with /VCrV/ symmetrical sequences were recorded (C = /b, d, g, v, ð, ɣ/ and V= /i, e, a, o, u/) up to 4 syllables in length and with varied stress position, e.g. *ˈmadra* ‘paddock’, *ˈivris* ‘hubris’. They were embedded in the carrier phrase [*i ˈleksi _ ˈine aˈpli*] ‘The word _ is simple’ and were repeated five times at a comfortable speaking rate by two male and three female Greek adult speakers. The total number of tokens was 750 (5 Vs x 6 consonants x 5 reps x 5 speakers). Additionally, rhotic production in /VCrV/ sequences with a voiced stop is compared to previously reported findings on /VCrV/ sequences with a voiceless stop C=/p, t, k/ (375 tokens; Nicolaidis & Baltazani 2011).

Acoustic data were recorded on a digital recorder (Marantz PMD 660) with a Røde NT1-A cardioid condenser microphone. In addition, EPG and acoustic data were recorded simultaneously using the British EPG system marketed by Articulate Instruments. Artificial palates in this system have 62 electrodes on their surface, distributed in eight rows. The front four rows correspond to the alveolar zone (alveolar region = rows 1 and 2; postalveolar region = rows 4 and 5) and the back four rows to the palatal zone (Recasens et al. 1993). The Praat software (Boersma & Weenink 2020) was used for the acoustic analysis and the ArticAssist software for the articulatory analysis.

For all /VCrV/ sequences we measured the durations of all segments and the vocoid as well as the F1, F2 formants of both vowels and the vocoid. For the articulatory analysis, we annotated the first EPG frame of maximum contact/constriction in the front four rows during the phase of rhotic constriction. The following measures were calculated: (a) the total number of contacts for the entire palate (global total), (b) the Centre of Gravity for the front four rows (front COG: quantifies how anterior lingual placement is), (c) a mean lateral measure for the front four rows (FLM: quantifies how constricted or open the articulation is), (d) percentage frequency of electrode activation of the entire palate over five repetitions for each rhotic.

Rhotics were also categorized in terms of the detailed phonetic characteristics of the constriction and vocoid phases. All constriction categories noted in Table 1 were represented in the current data set. For the vocoid, there were no tokens with voiceless vocoids as found in voiceless consonantal contexts (Nicolaidis & Baltazani 2014). Instead, in the voiced context we added a category labeled ‘weak’ displaying reduced or no energy in all formants or in the higher formants, and low amplitude in the acoustic waveform.

Factorial analyses of variance on the different acoustic and articulatory measures were carried out with subject (1-5), consonantal manner (stop-fricative), consonantal place (labial, dental, velar), vowel context (i, e, a, o, u) as factors. The effect of voicing of the preceding stop context was also tested (voiceless-voiced). For the acoustic data, rhotic type of realisation for the constriction (1-5) and vocoid (1-3) were also included as factors. All main effects and interactions were tested.

3 Results

3.1 Examples of constriction categories

We showcase different realisations of the rhotic production using acoustic and articulatory information below. Tokens involved only one constriction indicating tap production (except for a single token of a trill). The palatograms in Figure 1 show two examples of complete constriction in the alveolar zone (black squares correspond to activated electrodes due to contact of the tongue on the palate, white ones indicate no contact; complete constriction is shown by the presence of activated electrodes across the alveolar zone). The acoustic data confirm that there is a stop-like interval in both examples and provide details on possible variation: in (a) the constriction is followed by a burst, in (b) there is no burst after the constriction.

(a)

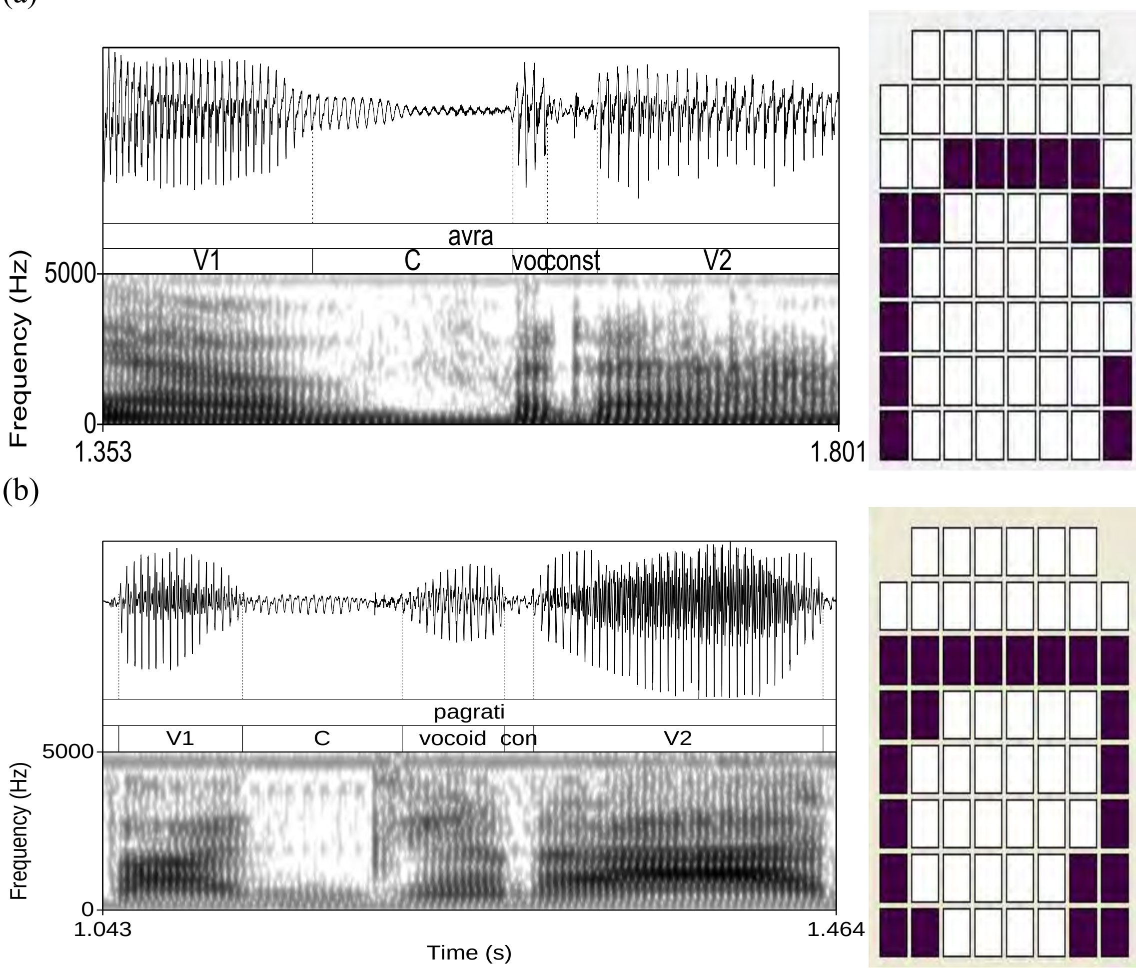


Figure 1. The sequence (a) /vr/ in /a'vra/ and (b) /gr/ in /pa'grati /with EPG palatograms at the frame of maximum contact/constriction during /r/. See text for details.

Figure 2 shows two examples with incomplete linguo-palatal constriction in the alveolar zone. The acoustic data show that in (a) the slightly open constriction is produced with a stop-like interval without a burst. A very open articulation and presence of formant structure during the constriction indicates the production of an approximant in (b).

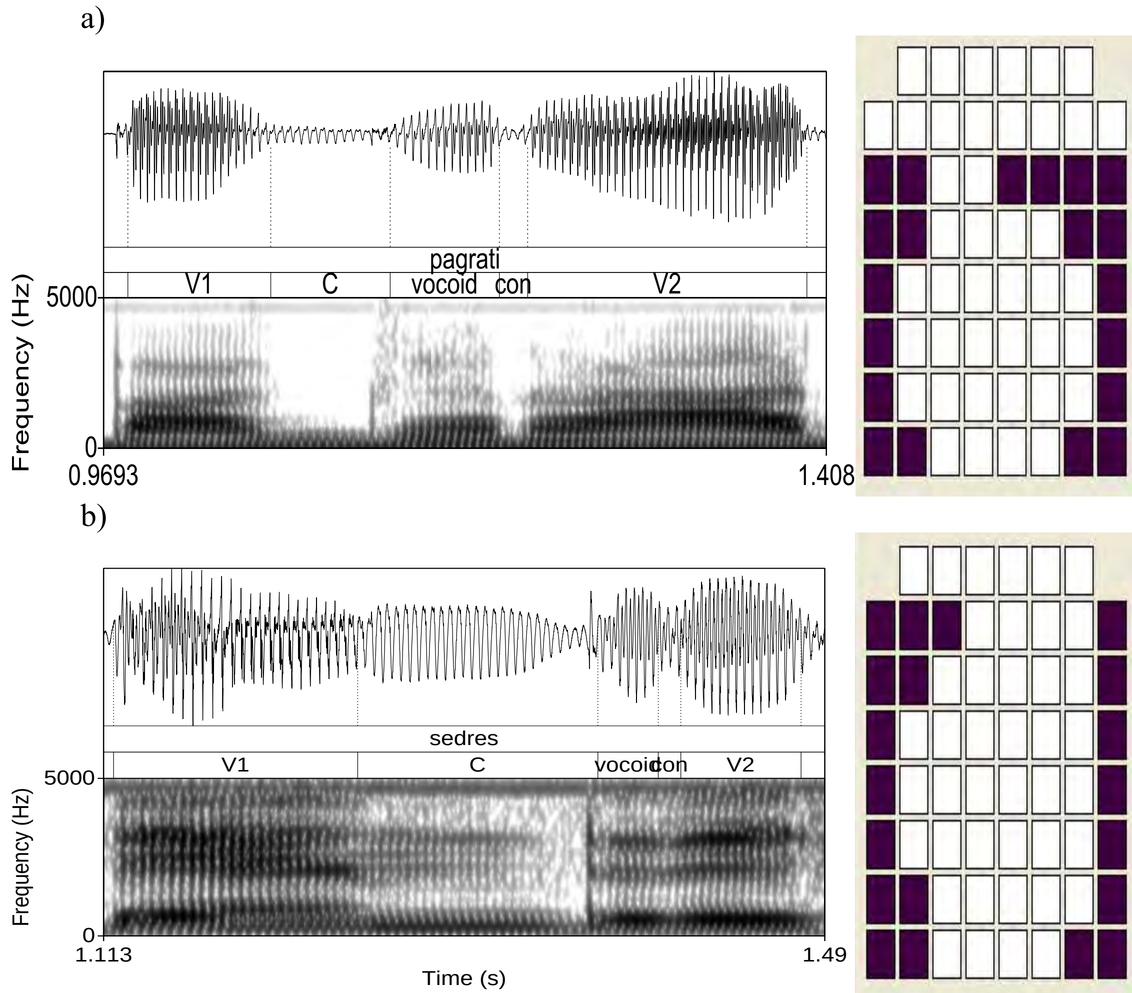


Figure 2. The sequence (a) /gr/ in /pa'grati/ and (b) /dr/ in /'sedres / with EPG palatograms at the frame of maximum contact/constriction during /r/. See text for details.

Some tokens with incomplete constriction in the alveolar zone and presence of noise during the constriction phase of the rhotic were also found (Figure 3) indicating an assibilated production.

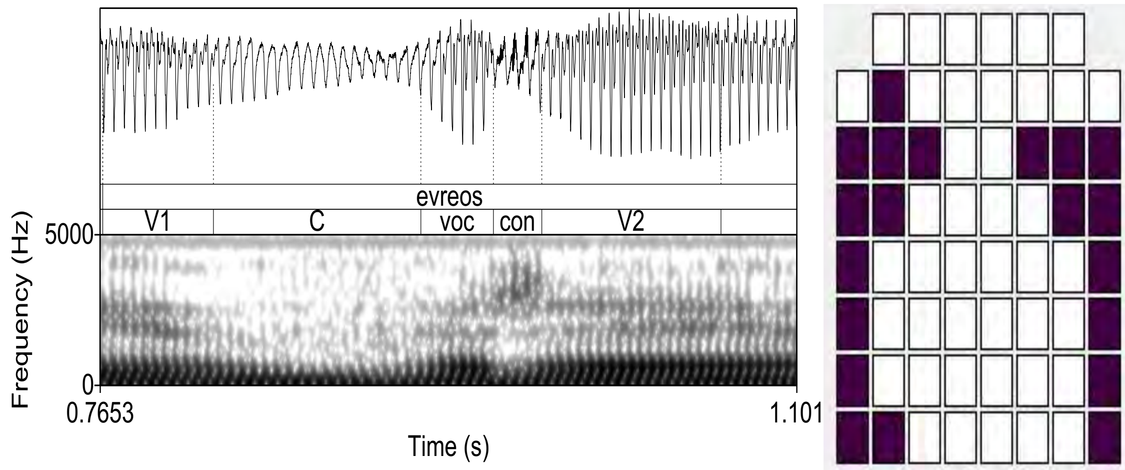


Figure 3. The sequence /vr/ in /e'vreos/ and EPG palatogram at the frame of maximum contact/constriction during /r/. See text for details.

An analysis of the constriction category distribution based on the acoustic data (Figure 4) revealed that 40.13% of the tokens were produced with a silent interval followed by a burst (cf. Figure 1a), 32.27% with a silent interval without a burst (cf. Figure 1b), 12.8% with an approximant-like constriction (cf. Figure 2b) and 14% assibilated tokens (cf. Figure 3). When these categories are combined with articulatory information on presence of complete/incomplete closure (Table 2), the complete-to-incomplete constriction ratio is approximately 42% / 58%.

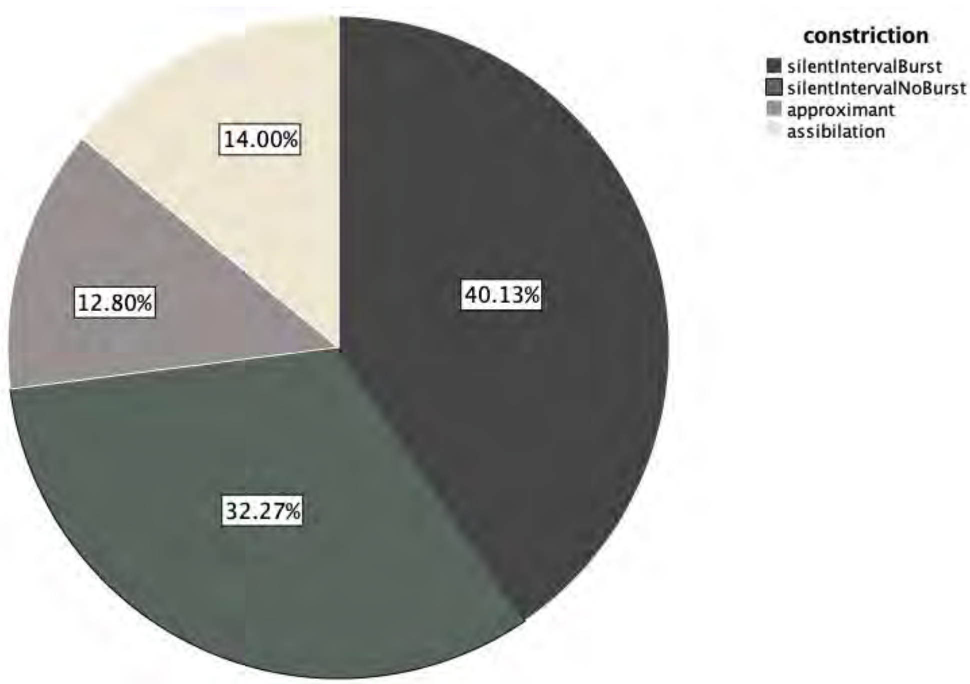


Figure 4. The distribution of constriction categories for tap productions in voiced /Cr/ clusters (based on acoustic data).

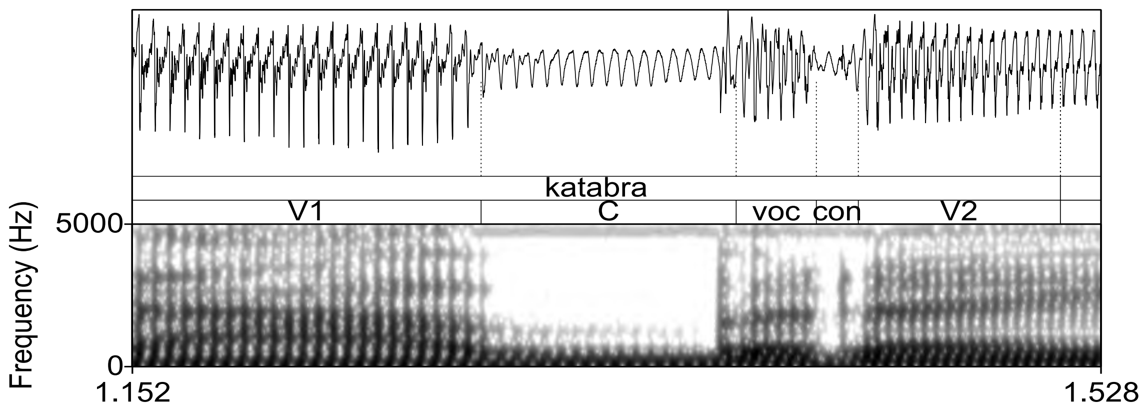
	KN	AT	RP	MM	TP
Voiced stop-r	49/75	57/75	60/75	33/75	16/75
Voiced fricative-r	55/75	54/75	65/75	30/75	19/75
Total	104/150	111/150	125/150	63/150	35/150

Table 2. Number of rhotics produced with incomplete constriction in voiced /stop-r/ and /fricative-r/ clusters for all speakers.

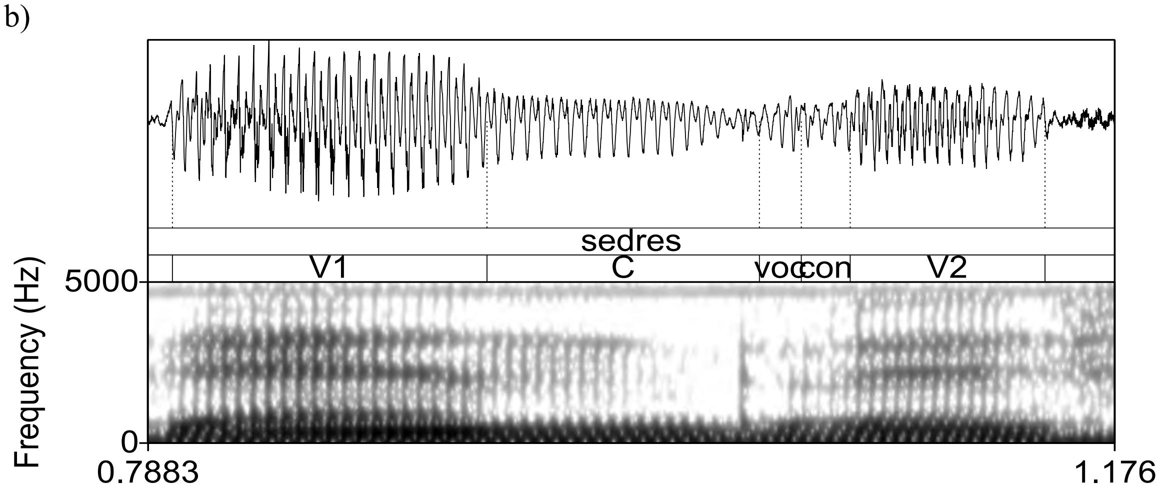
3.2 Examples of vocoid categories

The rhotic typically involves the presence of a vocoid (98% of tokens). There was variability in vocoid production including modal or breathy phonation (Figure5a), weak production (5b) or, rarely, absence of the vocoid (5c).

a)



b)



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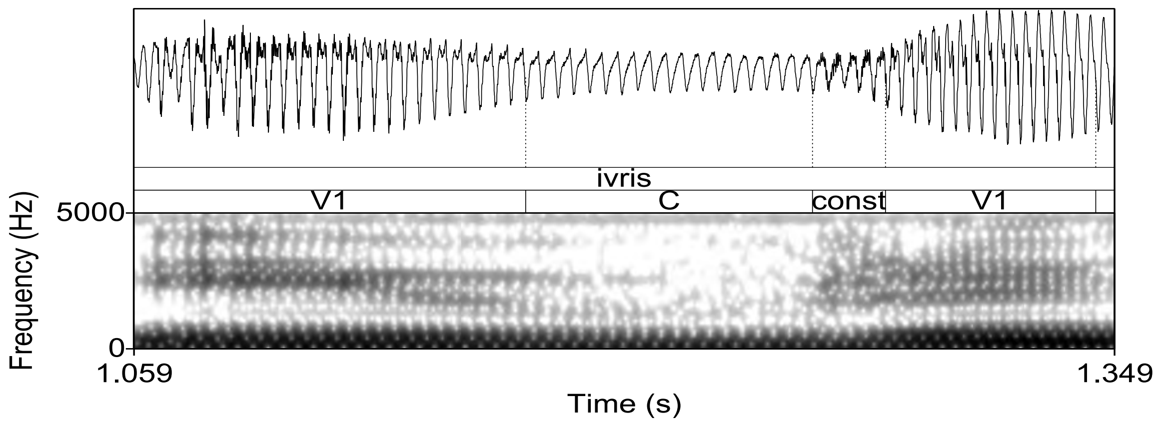

Figure 5. The sequence (a) /br/ in /ka'tabra/ illustrates modal production with presence of formant structure and high amplitude;(b) /dr/ in /'sedres/, weak production with reduced amplitude; (c) /vr/ in /'ivris/, absence of vocoid.

3.3 Articulatory variability: EPG data

The analysis of articulatory data showed variability in rhotic production as a function of the vocalic and consonantal context, and speaker. Anterior displacement, measured with the front CoG measure, was affected by the vocalic context in the order i>e>u>a>o, i.e. the rhotic was more fronted in the environment of front vowels compared to back or open vowels (Figure 6, $F(4, 372)=19{,}273$, $p<.0001$ for /fricative-r/ (/Fr/) clusters, $F(4,374)=18{,}366$, $p<.0001$ for /stop-r/ (/Sr/) clusters); post-hoc analyses showed no significant differences in tongue placement in the /u, a, o/ contexts for the /Fr/ clusters and between /e, u/, /u, a/ and /a, o/ for the /Sr/ clusters.

Figure 6. EPG palatograms displaying percentage frequency of electrode activation over five repetitions at the first frame of maximum contact/constriction in /br/ and /gr/ clusters in all vocalic contexts.

The vocalic context also influenced the total amount of lingual contact on the palate. The largest amount of contact was present in the context of the high vowel /i/ and the least in the context of /a/ (/Fr/: $F(4, 372)=61{,}520$, $p< .0001$); /Sr/: $F(4, 374)=64{,}437$, $p<.0001$).

There was also variation in the rhotic due to the place of articulation of the consonantal context (Front CoG, /Fr/: $F(2, 372)=112{,}434$, $p<.0001$; /Sr/: $F(2, 374)=4{,}625$, $p<.011$). The rhotic was generally more fronted in the context of a dental consonant, compared to the labial and velar contexts. Post-hoc analyses showed that for the /Fr/ clusters, contact was significantly more fronted in the context of /ð/ compared to /v, ɣ/ (ð>v=g; Figure 7); for the /Sr/ clusters contact was significantly more fronted in the context of /d/ compared to /b/ but not to /g/.

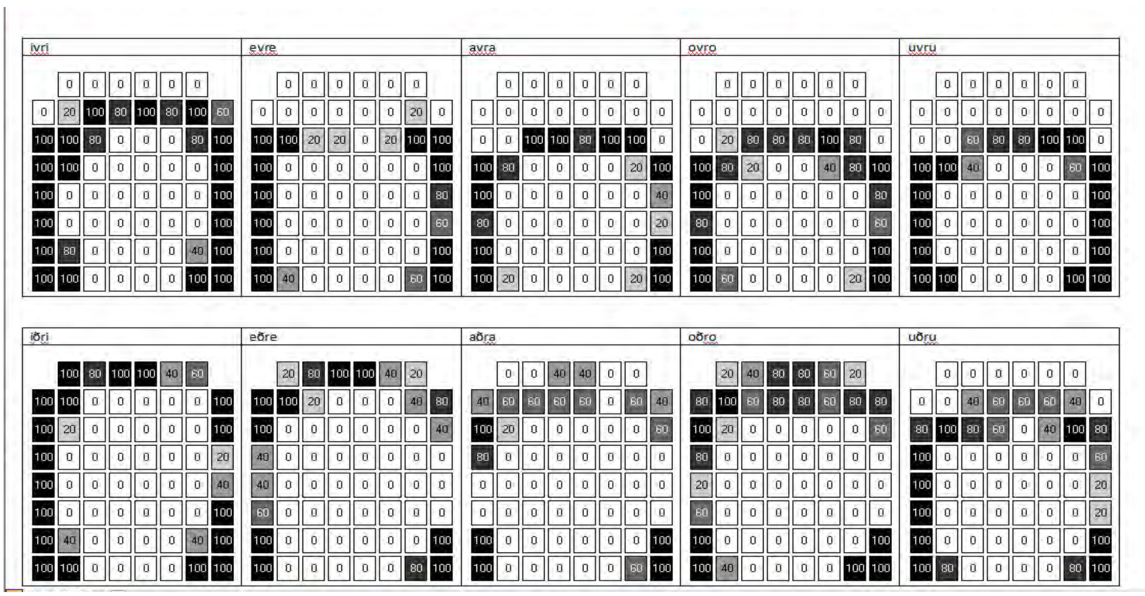

Figure 7. EPG palatograms displaying percentage frequency of electrode activation over five repetitions at the first frame of maximum contact/constriction for the rhotic in /vr/ and /ðr/ clusters in all vocalic contexts.

In addition, the manner of articulation of the consonant preceding /r/ (stop vs. fricative) influenced the rhotic production. More lingual contact on the palate was present for the rhotic in the environment of a stop than a fricative (global total: $F(1, 747)=7268$, $p<.007$). The consonant by manner interaction showed that more fronted and more constricted productions were found in the environment of the dental fricative compared to the dental stop context (Front CoG: $F(2, 747)=33608$, $p<.0001$; FLM: $F(2,747)=81{,}562$, $p<.0001$); variability was evident for the labial and velar places of articulation.

There was significant speaker variability in the total amount of contact, place of articulation and degree of constriction in the fricative and stop clusters (/Sr/ global total $F(4,374)=91{,}981$, $p<.0001$, front CoG $F(4,373)=72941$, $p< .0001$, FLM $F(4, 374)=59156$, $p< .0001$; /Fr/ global total $F(4, 372)=57{,}305$, $p< .0001$, front CoG $F(4, 372)=126725$, $p< .0001$, FLM $F(4, 372)=83263$, $p< .0001$). In general, speaker TP had more anterior placement, least contact on the palate and most constricted alveolar contact than the rest of the speakers in both types of clusters. Speaker RP had most linguo-palatal contact and most retracted placement across speakers; she also had the least constricted contact in the /Sr/

clusters (Figure 8).

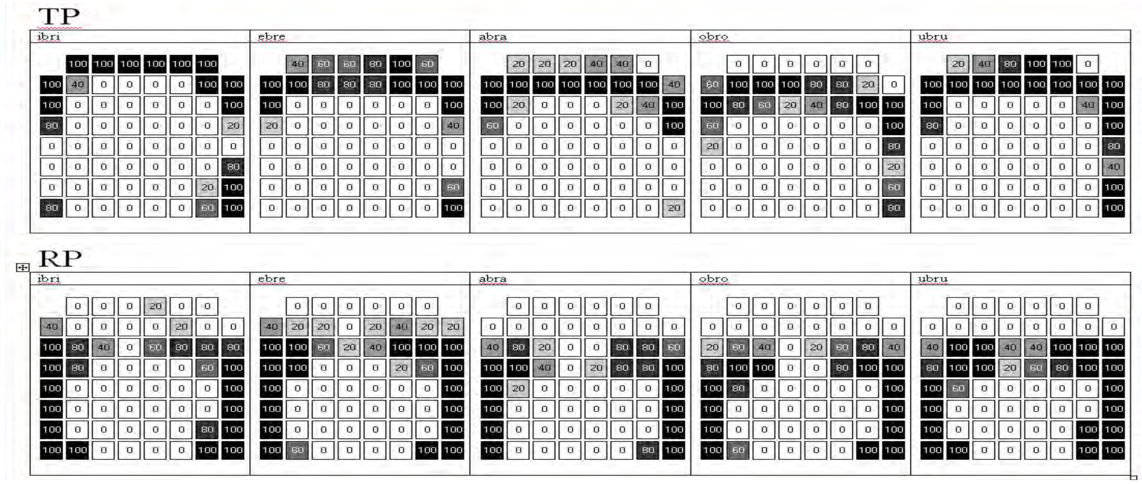

Figure 8. EPG palatograms displaying percentage frequency of electrode activation over five repetitions at the first frame of maximum contact/constriction for the rhotic in /br/ clusters in all vocalic contexts for speakers TP and RP.

Finally, the effect of voicing of the preceding consonant was examined by comparing the voiced /stop-r/ contexts with the voiceless /stop-r/ contexts reported in Nicolaidis & Baltazani (2011). More contact for the rhotic was found in the voiceless than voiced stop environment (Global Total F(1,748)=36,091, p<.0001). In addition, more anterior contact was found for /r/ in the voiceless than voiced context (Front COG F(1,748)=30,587, p<.0001; Figure 9).

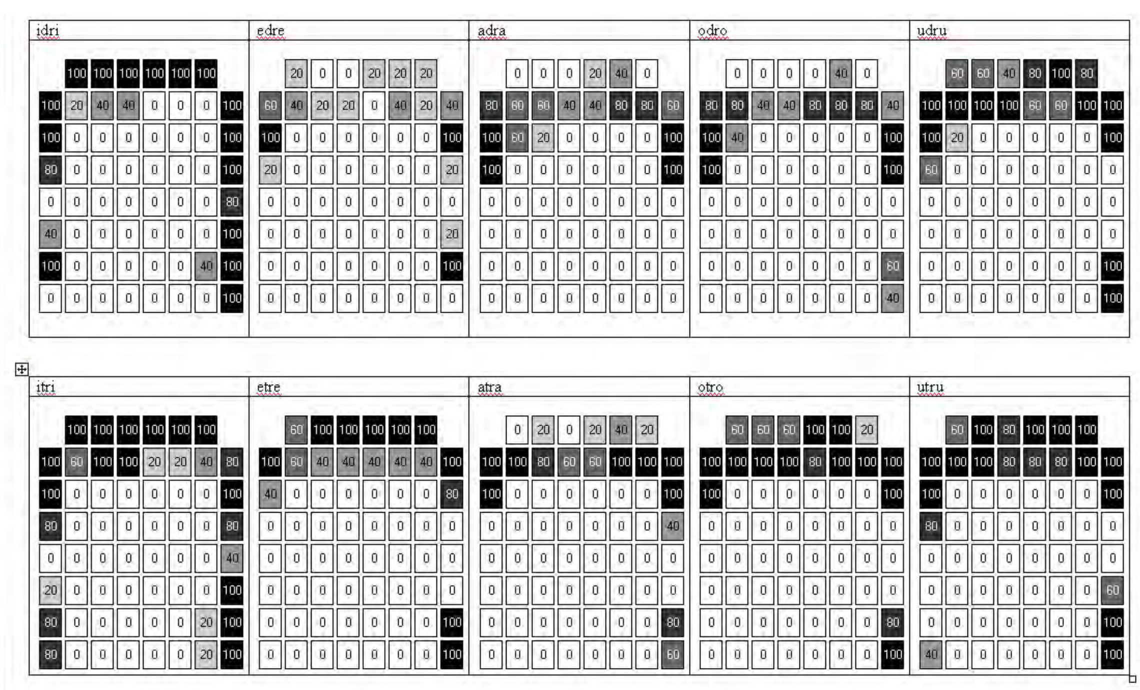

Figure 9. EPG palatograms displaying percentage frequency of electrode activation over five repetitions at the first frame of maximum contact/constriction for the rhotic in /dr/ clusters and /tr/ clusters in all vocalic contexts.

3.4. Acoustic variability

3.4.1. Duration

Across all conditions, the vocoid (M=37.9 ms, SD=16.6) was almost twice as long as the constriction (M=22.9 ms, SD=7.7). The manner of articulation of the contextual consonant had no effect on the constriction duration ($M_{[stop]}$=22.5ms, $M_{[fricative]}$=23.2ms, $F(1, 742)=1.392$, $p=.238$), but it did affect the vocoid duration ($M_{[stop]}$=34.7ms, $M_{[fricative]}$=41.2ms, $F(1, 742)=29.730$, $p<.001$; Figure 10).

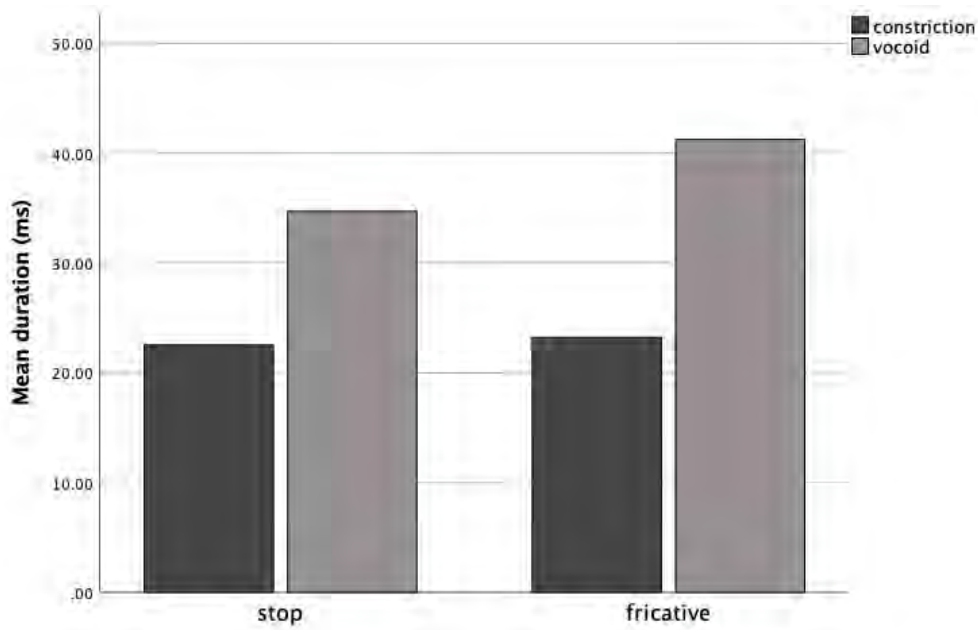

Figure 10. Duration of the constriction and the vocoid in the context of voiced stop and fricative consonants.

The data also indicate significant duration differences in the constriction ($F(3, 740)=59.01$, $p<.0001$) and vocoid ($F(2, 741)=67.15$, $p<.0001$) phases for the different realisation categories (Figures 11, 12). Post-hoc analyses showed that a silent interval followed by a burst was the longest while in very open, approximant-like tokens constriction was the shortest (silent-interval-plus-burst>assibilation=silent-interval-without-burst>approximant). In addition, vocoid duration was the longest in modal/breathy tokens and the shortest in weak vocoids.

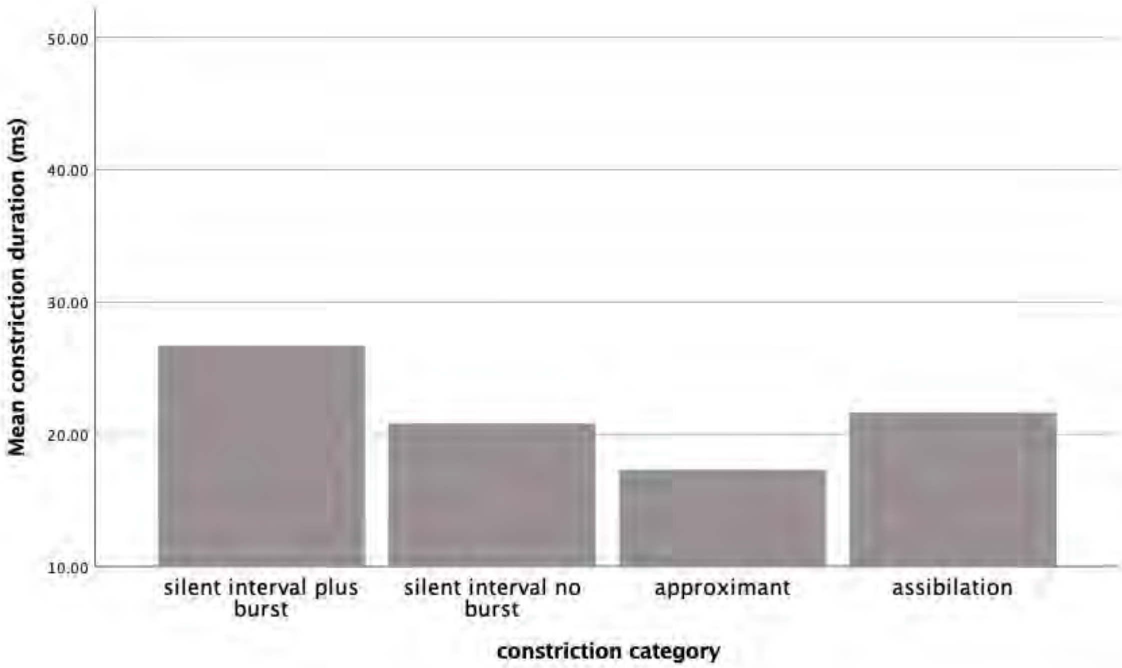

Figure 11. Duration of the constriction across the different constriction categories.

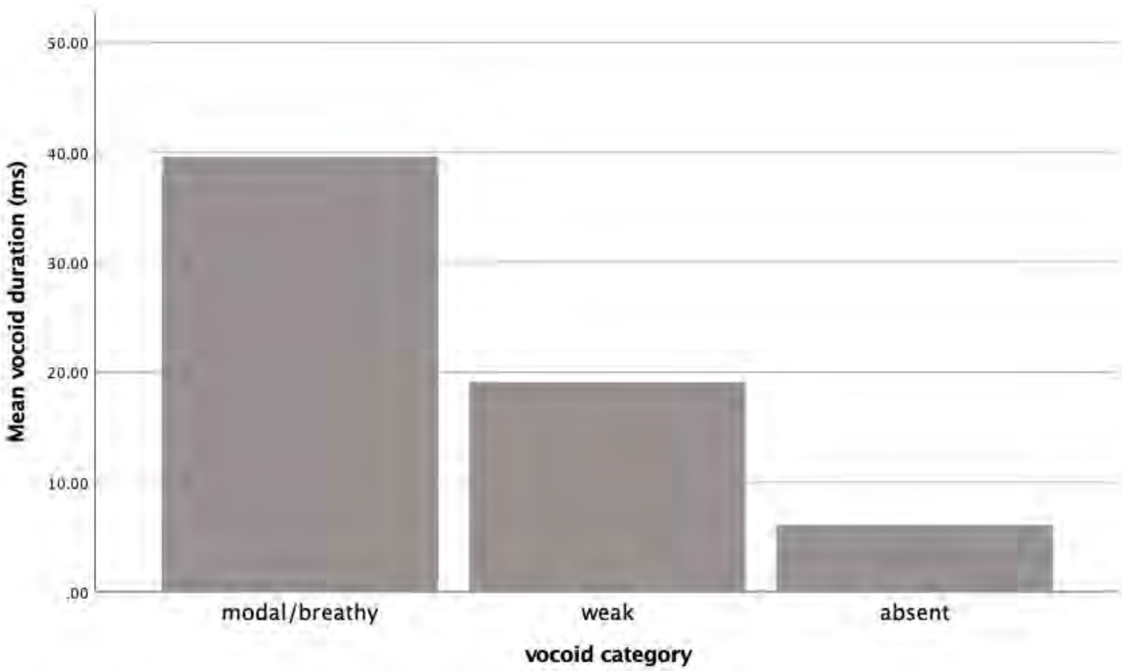

Figure 12. Duration of the vocoid across different vocoid categories.

The effects of several factors on the rhotic duration were examined separately for the stop and fricative consonantal contexts. The constriction duration was significantly affected by speaker (/Sr/ ($F(4, 350)=24.97$, $p<.0001$; /Fr/ $F(4, 356)=12.334$, $p<.0001$). An effect of consonantal place of articulation was found only for fricative contexts (/Fr/ $F(2, 356)=3.618$, $p=.006$, velars=dentals>labials), while no such effect emerged for stop contexts (/Sr/ $F(2, 350)=2.035$, $p=.139$; Figure 13). Finally, an effect of vocalic context was found: rhotic constriction duration was longest in the environment of the high vowels /i/ and /u/ (/Sr/ $F(4, 350)=15.072$, $p<.0001$, i>u>e=o>a; /Fr/ $F(4, 356)=19.187$, $p<.0001$, i>u=o>e=a).

The vocoid duration was significantly affected by all the above factors, i.e., speaker (/Sr/ $F(4, 350)=53.255$, $p<.0001$; /Fr/ $F(4, 356)=29.044$, $p<.0001$), consonantal place of articulation (/Sr/ $F(4, 350)=106.880$, $p<.0001$, velars>labials=dentals; /Fr/ $F(2, 356)=99.233$, $p<.0001$; velars>dentals>labials; Figure 13) and vocalic context (/Sr/ $F(4, 350)=9.189$, $p<.0001$; u>i=o=e=a; /Fr/: $F(4, 356)=6.152$, $p<.0001$; a=u>i=e=o).

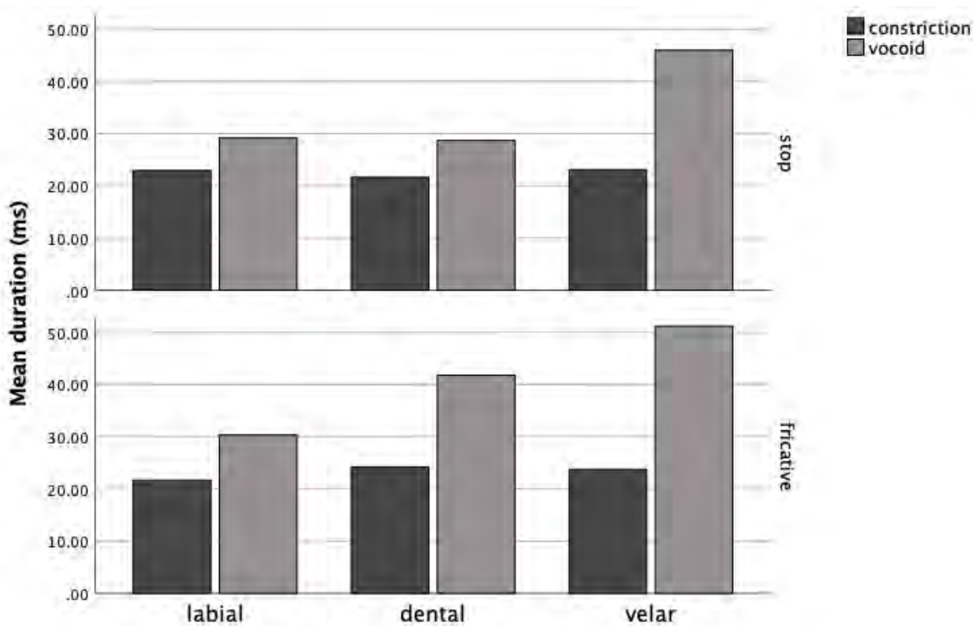

Figure 13. The duration of the constriction and the vocoid by place and manner of articulation.

3.4.2 Formant frequencies

Our analysis showed that there was an effect of speaker on vocoid formants, F1 and F2 (SF1[1,2], $F(2, 345)=160.406$, $p<.0001$; SF2, $F(2, 345)=24.767$, $p<.0001$; FF1, $F(4, 288)=231.738$, $p<.0001$; FF2, $F(4, 291)=65.637$, $p<.0001$). There was also an effect of the vocalic context, with both F1 and F2 having values similar to those of the contextual vowel, but more centralized (Figure 14 for fricative contexts) (SF1, $F(4, 329)=147.007$, $p< .0001$; SF2, $F(4, 329)=333.037$, $p<.0001$; FF1, $F(4, 288)=317.345$, $p<.0001$; FF2, $F(4, 291)=191.118$, $p<.0001$).

[1]Abbreviations: SF1 = Stops, F1 formant. SF2 = Stops, F2 formant. FF1 = Fricatives, F1 formant. FF2 = Fricatives, F2 formant.

[2]Due to problems in the retrieval of data for stop contexts from one of the two male speakers, the analysis of vowels in stop contexts was carried out for the three female speakers only.

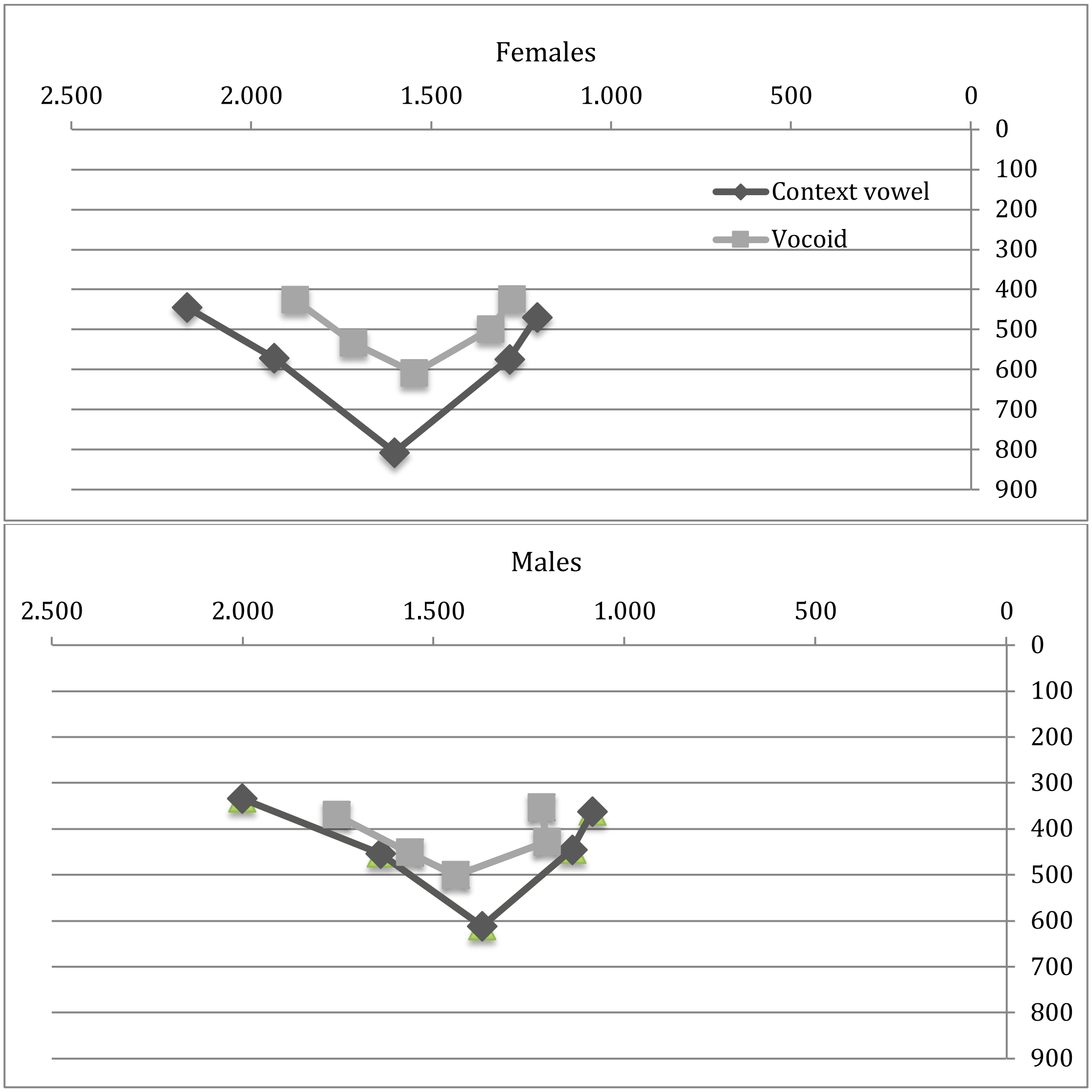

Figure 14. Comparison between the vocoid and the contextual vowel in the context of fricative consonants, for female (top) and male speakers (bottom).

3.4.3 Effect of voicing on rhotic production

The comparison between /r/ in voiced stop contexts and /r/ in voiceless stop contexts (Nicolaidis & Baltazani 2011) showed that in both voicing conditions the vocoid (M=29.7ms, SD=14.9) is longer than the constriction (M=22.9ms, SD=7.8; Figure 15). This difference is considerably larger in voiced consonant contexts than in voiceless ones, because the vocoid is significantly longer in voiced (M=34.7, SD=15.8) compared to voiceless (M=24.7ms, SD=12.2) contexts (F(1, 739)=92.25, p<.0001), while the constriction is shorter ($M_{[voiced]}$=22.5ms, SD=7.8; $M_{[voiceless]}$=23.2ms, SD=7.5), but not significantly so (F(1, 740)=1.79, p=.181).

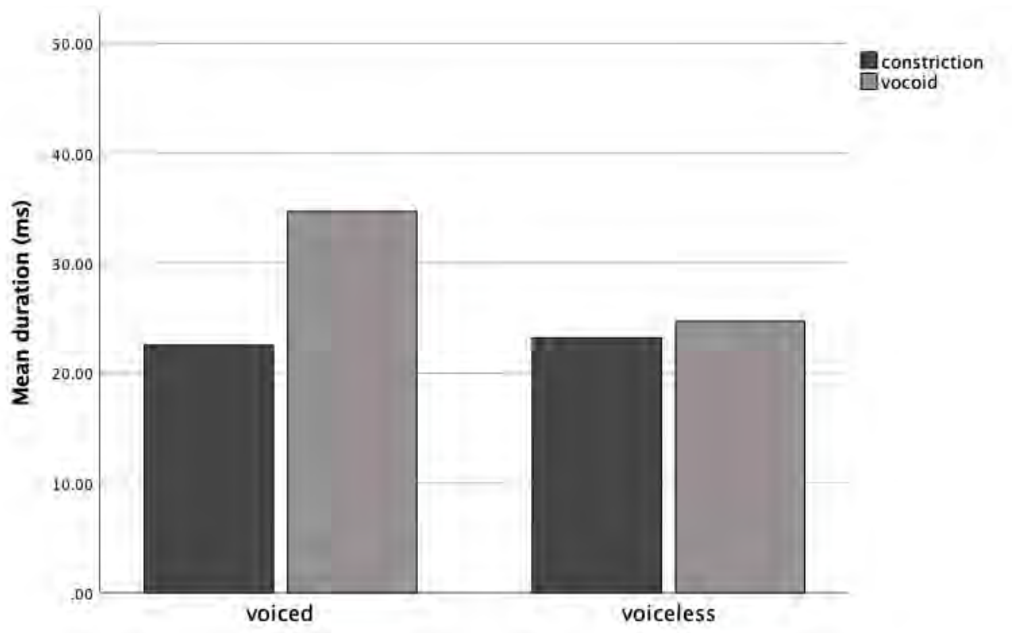

Figure 15. Duration of the vocoid and constriction phases of the rhotic in the context of preceding voiceless or voiced stops.

Furthermore, the articulation of the constriction was affected by the voicing of the preceding consonant ($\chi^2(4)$=34.5, p<.0001; Figure 16). A larger number of stop-like constrictions followed by a burst occurred in voiceless contexts, while in voiced contexts there occurred more tokens with stop-like constriction but no burst, assibilated tokens or approximants, and one trill production was found.

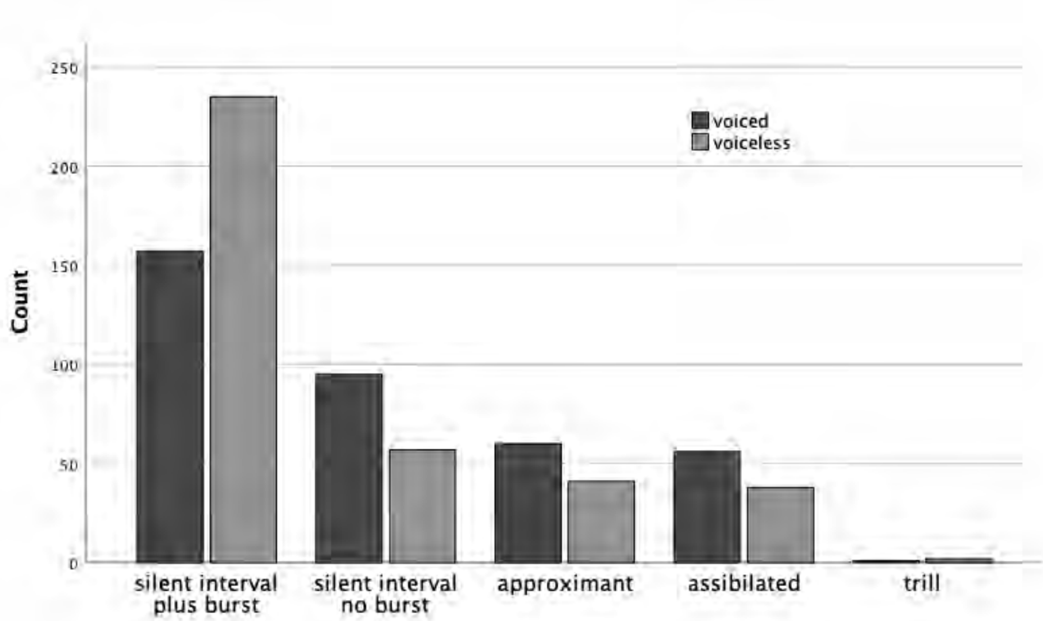

Figure 16. Number of tokens for different constriction categories in voiced and voiceless consonant contexts.

Finally, consonantal voicing affected the vocoid characteristics ($\chi^2(2)=14.4$, $p<.001$; Figure 17), with more modal/breathy vocoids found in voiced than voiceless stop contexts[3].

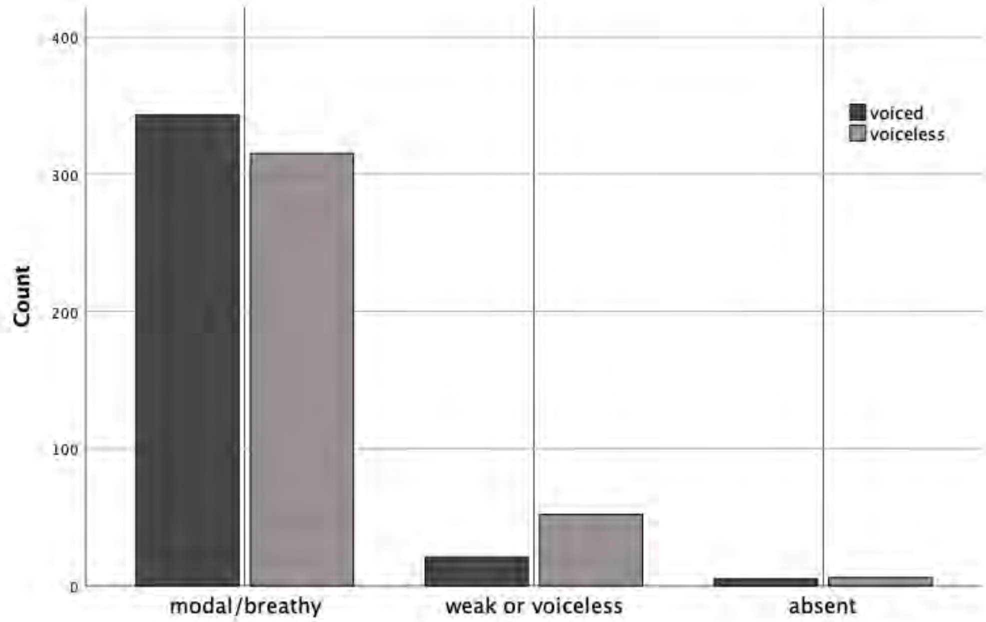

Figure 17. Number of tokens produced with different types of vocoids in voiced and voiceless stop contexts (see text for details).

3 Discussion

In agreement with previously reported findings, this study has shown that the Greek rhotic is a tap produced with a single constriction phase and a vocoid. Its production is characterised by large spatio-temporal variability manifested in the constriction and vocoid phases and influenced by the consonantal and vocalic context, and the speaker.

Rhotic constriction varied in degree of stricture along a continuum ranging from complete constriction to gradually weaker productions and ending in very open approximant realisations. Depending on the aerodynamic conditions and the degree of approximation of the lingual gesture to the alveolar ridge, productions can involve frication or approximant realisations with presence of formant structure throughout the rhotic constriction. EPG data showed that 58% of tokens were produced with incomplete constriction corresponding to a stop-like constriction without a burst, an approximant or assibilated production as evident on the acoustic data. Place of articulation also varied ranging from very anterior alveolar productions (1st or 1st-2nd rows on the EPG palate) to retracted alveolar or postalveolar productions (3rd or 3rd-4th rows).

[3] As explained in section 2, we added the category 'weak' vocoid in the present study, shown in the middle pair of bars, Figure 17, together with 'voiceless' vocoid which occurred in voiceless stop contexts (no voiceless vocoids were found in voiced contexts).

The tap gesture showed clear evidence of coarticulatory effects from the vocalic and consonantal environments with more anterior production in front vowel contexts and in dental consonantal contexts. More linguopalatal contact and more anterior contact for the /r/ in the voiceless than voiced stop context may also be interpreted to reflect coarticulatory effects from the consonantal context. Typically, larger linguopalatal areas and more anterior contact has been reported for voiceless than voiced stops across several languages (e.g. Kochetov 2014), with the different production characteristics of the voiced stops related to supra-laryngeal cavity expansion implemented to facilitate voicing. Similar linguopalatal behavior for the /r/ in the voiceless versus voiced stop context suggests influence from the preceding consonant and carryover coarticulatory effects. In addition, more rhotics with incomplete constriction in a voiced stop context (58%) compared to a voiceless one (44% in stop contexts; Nicolaidis & Baltazani 2011), may also relate to reported reduced occlusions for voiced compared to voiceless stops possibly reflecting differences in articulatory force (Kochetov 2014).

Vocoid production was characterised by similar but more centralized formant frequency values compared to the nuclear vowel (cf. Quilis 1993) as well as context-induced variability: greatest vocoid duration was found in velar contexts (cf. Bradley & Schmeiser 2003), possibly due to the involvement of the tongue back and tongue tip/blade articulators for the velar and alveolar gestures and their timing during the /Cr/ cluster.

The rhotic structure comparison in voiced and voiceless stop environments revealed an interesting trade-off relationship in duration: while the vocoid was significantly longer in voiced than voiceless contexts, the constriction was longer (but not significantly so) in voiceless than voiced ones (cf. Recasens & Espinosa 2007). This finding suggests possible production constraints due to the coordination between different articulators, especially the laryngeal and oral ones, as a shorter vocoid following a voiceless stop could relate to a delay in the initiation of phonation. The presence of voiceless vocoids in voiceless contexts supports this explanation and can be accounted for by coarticulation. In the voiced stop environment, voicing continues from the stop to the vocoid. Interestingly a compensatory relationship between vocoid and constriction duration was observed suggesting a temporal adjustment between the constriction and vocoid phases of the rhotic, i.e. longer vocoid was accompanied by shorter constriction and vice versa. The acoustic data showed that in voiceless contexts the rhotic is produced with silent interval plus burst more frequently than in voiced contexts (section 3.2.3). This type of constriction was significantly longer and may be interpreted as a “stronger” articulation resulting from aerodynamic and production constraints.

Previously we argued that the presence of the vocoid is due to a vocalic gesture upon which the rhotic is superimposed (cf. Öhman 1966). The systematic presence of a vocoid in the current study strengthens this claim. The strongest support comes from the presence of the vocoid even in phrase-initial position (Nicolaidis & Baltazani 2014) where /r/ occurs as a singleton, without an adjacent consonant affecting its articulation, which strongly suggests that the vocoid is an intrinsic rhotic component found in all contexts. We hypothesise that the execution of the short ballistic gesture of the tap needs to be embedded on this rhotic-specific vocalic gesture. This hypothesis also accounts for the spatio-temporal variability of both the vocoid and constriction phases due to coarticulatory effects in different contexts.

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