Available online at www.sciencedirect.com
ScienceDirect
Journal of Phonetics 37 (2009) 189–211
Journal of Phonetics
www.elsevier.com/locate/phonetics

Acoustics and perception of velar softening for unaspirated stops

Daniel Recasens[a,b,*], Aina Espinosa[a,b]

[a]Departament de Filologia Catalana, Universitat Autònoma de Barcelona, Bellaterra, Barcelona, Spain
[b]Laboratori de Fonètica, Institut d'Estudis Catalans, c/Carme, 47, Barcelona 08001, Spain

Received 2 July 2008; received in revised form 16 January 2009; accepted 20 January 2009

Abstract

This paper provides articulatory, acoustic and perceptual data in support of the hypothesis that the velar softening process through which /k/ becomes /tʃ/ is based on articulation rather than on acoustic equivalence if operating on unaspirated stops. Production data for unaspirated /k/ are analyzed for five speakers of Majorcan Catalan, where the velar stop phoneme exhibits (alveolo)palatal or velar allophones depending on vowel context and position. Data on several parameters, i.e., contact anteriority and dorsopalatal contact degree, burst spectral peak frequency, energy and duration, and F2 and F3 vowel transition endpoints and ranges, suggest that /tʃ/ may have originated from (alveolo)palatal stop realizations not only before front vocalic segments but also before low and central vowels and word finally. Perception results are consistent with the production data in indicating that the most significant /tʃ/ perception cues are burst energy before /a, u/ and burst duration word/utterance finally. They also suggest that velar softening for unaspirated /k/ before front vocalic segments is triggered by an increase in burst frication energy and duration resulting from the narrowing of an (alveolo)palatal central channel occurring at stop closure release. These findings are in agreement with the existence of contextual and positional (alveolo)palatal stop allophones of /k/, and with evidence from sound change, in the Romance languages.

1. Introduction

1.1. Explanatory hypotheses of velar softening

Velar softening involves the replacement of /k/ by the alveolopalatal affricate /tʃ/ and even by the alveolar affricate /ts/ which may then give rise to the fricatives /ʃ/ and /s/, respectively. The affricate /tʃ/ is generally produced with the tongue blade at the central or back alveolar zone and possibly the tongue predorsum at the prepalate, and will be referred to as alveolopalatal rather than as palatoalveolar throughout this paper in view of data for the Catalan language reported in the literature (see Recasens & Espinosa, 2006). Illustrative examples of this velar softening process may be found in the Romance languages, e.g., Latin /ˈkɛnto/ CENTU 'one hundred' has evolved into [ˈtʃento] cento in Italian and into [sɛ̃] cent in French.

The change /k/> /tʃ/ is widely attested before front vowels and /j/ as in the case of the first Slavic palatalization and in Bantu, just before front vowels as in the case of the second Slavic palatalization, in Indo-Iranian and in Old English word initially, or just before /i/ as in Cowlitz Salish or before /j/ as in Chinese (Guion, 1996). As for the Romance language family, a first palatalization wave caused /k/ to become /tʃ/ (also /ts/) before front vowels and /j/ in all languages except for Sardinian which suggests that the process should be traced back to late Latin and must have been completed by the 5th century A.D.

The reason why velar softening is implemented preferably before front vocalic segments is consistent with the well-known fact that velar stops are articulated at a more anterior location in this contextual condition than before low and back rounded vowels and /w/. Indeed, closure location occurs generally at the rear hard palate and therefore, at the postpalatal or postpalato-velar regions for front velars, and at the soft palate or velar region for back

*Corresponding author at: Departament de Filologia Catalana, Faculat de Lletres, Universitat Autònoma de Barcelona, Bellaterra, Barcelona, Spain.
E-mail address: daniel.recasens@uab.es (D. Recasens).

0095-4470/$ - see front matter
doi:10.1016/j.wocn.2009.01.001

velars. Palatographic and X-ray data indicate that this contextual variation in place of articulation for velars is widespread among the world's languages, i.e., it occurs in languages as diverse as English (Keating & Lahiri, 1993; Liker & Gibbon, 2007), Czech, Hungarian (Keating & Lahiri, 1993), Telugu (Reddy, 1981) and French (Corneau, Soquet, & Demolin, 2000), as well as in the Eastern Catalan dialect (Recasens & Pallarès, 2001).

Two different explanatory hypotheses based on articulation (Section 1.1.1) and on acoustic equivalence (Section 1.1.2) have been put forth in order to account for velar softening.

1.1.1. Articulation-based hypothesis

The articulation-based hypothesis has been the prevailing explanation of velar softening during the 20th century and even earlier. Among other scholars, Romance phoneticians and dialectologists in the past have argued that velar softening takes place after an increase in closure fronting for front velar stops causing a change in place of articulation from postpalatal or postpalato-velar to mediopalatal, prepalatal, alveolopalatal or even alveolar. After this change in place, the stop burst, which is composed of a burst spike, a frication phase and an aspiration period if available, is integrated as the frication component of an affricate (Anttila, 1972, p. 73; Grammont, 1971, p. 214; Hock, 1986, p. 76; Rousselot, 1924–1925, pp. 607–631). In summary, the articulation-based hypothesis claims that velar softening (a change in manner, from stop to affricate) is necessarily preceded by velar palatalization (a change in place of articulation, from velar to a more anterior articulation approaching the closure and constriction location for /tʃ/). In this paper, the terms 'velar softening' and 'velar palatalization' will be kept separate. The stop realizations generated through velar palatalization will be referred to as (alveolo)palatal, and transcribed as [c] if voiceless and as [ɟ] if voiced, in line with the fact that they show most typically two articulatory patterns: alveolopalatal involving a simultaneous alveolar and palatal closure; and palatal proper with closure occurring exclusively at the palatal zone (Recasens, 1990). The main articulator is the tongue dorsum if the articulatory outcome is palatal, and the blade and predorsum if it is alveolopalatal.

In support of the articulation-based hypothesis, there is a good deal of palatographic data showing that (alveolo) palatal stop realizations derived from /k/ differing in closure fronting degree may occur before front vocalic segments in languages and dialects as diverse as Greek (Nicolaidis, 2001, pp. 71–73), Romanian (Dukelski, 1960, p. 44), Majorcan Catalan (Recasens & Espinosa, 2006) and Occitan (Maurand, 1974, pp. 116, 131–132). These realizations range auditorily from more /k/-like to more /t/-like, which accounts for why phoneticians have often used slightly different phonetic symbols in order to transcribe those sound qualities (Rousselot, 1924–1925). Accordingly, replacements such as [ke'ki] celui-ci 'this one' by [ke'ti] in Occitan could very well arise from the existing form [ke'ci] in the same dialect (Bouvier, 1976, p. 83).

Moreover, whenever enough frication is generated through the lingual constriction at stop release, the affricate outcomes of [c] through velar softening may exhibit different degrees of closure fronting which parallel those for the (alveolo)palatal stop (Scripture, 1902). Thus, the resulting affricate may vary from palatal ([tç]) to alveolopalatal ([tʃ]) to alveolar ([ts]) depending on whether closure for [c] occurs at the palatal, alveolopalatal or alveolar zone, respectively. Supporting evidence derives from the presence of these affricate types in the same or close dialectal areas, often cooccurring with realizations of [c]: [c], [tç], [tʃ] and [ts] in Rhaetoromance (see Section 1.2.2); [c] and [tʃ] in Francoprovençal ([ky], [c(j)y], [tʃy] cul CULU 'bottom'; Gardette, 1967–1984, map 1112); [c] in Standard Modern Greek but [tç] in Cretan Greek and [tʃ] in Cypriot Greek (Trudgill, 2003, p. 54).

1.1.2. Acoustic equivalence hypothesis

A more recent proposal, the acoustic equivalence hypothesis, claims that the categorization of front velars as affricates has not taken place through additional closure fronting. If velar softening is achieved through assimilation via an (alveolo)palatal stop, it remains unclear why such a stop should be articulated so much further forward than the vocalic segment causing the assimilatory process to take place (Ohala, 1992). Ohala and colleagues argue instead that velar softening is caused by acoustic equivalence between the front velar stop burst and the /tʃ/ frication noise which, as found for several languages, share a spectral peak frequency at about 2500–3500 Hz (English: Guion, 1998; Stevens, 1998, p. 416; Zue, 1980; German, Polish, Catalan: Zygis, Recasens, & Espinosa, 2008). Acoustic similarity is enhanced by the high-frequency F2 vowel transition endpoints for both front /k/ and /tʃ/.

Evidence for this hypothesis is said to derive from the confusion of /ki/ with /ti/. This confusion has been reported to occur for English excerpts with either aspirated /k/ excised from utterance initial CV sequences (Winitz, Scheib, & Reeds, 1972) or else unaspirated /k/ excised from /ski/ after degradation of its 3000 Hz burst peak (Chang, Plauché, & Ohala, 2001). It should be noticed, however, that these perceptual experiments do not test velar softening proper since they do not show that /k/ may be replaced by /tʃ/. Indeed, there are at least two relevant differences between /t/ and /tʃ/ which suggests that an alternative explanation may be needed: the absence of sufficient frication noise at /t/ release, mostly if the stop is unaspirated; a substantial frequency difference between the spectral peak for the /t/ burst (at about 4000 Hz; Zue, 1980) and for the /tʃ/ frication component (at 2500–3500 Hz). Moreover, filtering important spectral information may render speech stimuli unnatural.

In a pioneering production and perception study, Guion (1998) has shown that front /k/ may be confused with /tʃ/ under specific methodological conditions, thus providing some evidence in support of the acoustic equivalence hypothesis. Presentation of natural speech perception stimuli containing a velar stop and the following vowels /i/, /ɑ/ or /u/ yielded /tʃ/ responses only if white noise was superimposed on them. Natural speech stimuli without noise overimposed did not yield any /tʃ/ responses. In these circumstances, /k/ before /i/ was confused mostly with /tʃ/ (35%), but also with /g/ (10%) and with /dʒ/ (12%) perhaps since the low signal-to-noise ratio used in the study (+2B) rendered these stimuli hard to categorize. As expected, /k/ before /ɑ/ yielded relatively few /tʃ/ responses (13%) and practically no confusions with /g/ or /dʒ/; unexpectedly high confusion percentages for /ku/ were attributed by the author to the front realization of /u/ in the Texan American English dialect of the speakers who provided the production data for the perceptual tests. A remarkable finding of Guion's study is that not only the high-frequency burst spectral peak but also VOT duration and, therefore, the duration of the burst frication and aspiration period, plays a relevant role in the implementation of velar softening (i.e., the longer the VOT period, the higher the percentage of affricate reponses).

1.2. Additional arguments in support of the articulation-based hypothesis

Descriptive, experimental and sound change data reported above appear to be in support of an articulatory motivation of velar softening at least for Romance and other language families. The main argument is the presence of (alveolo)palatal realizations of front /k/ and the fact that these realizations may cooccur synchronically with affricates in ways which are consistent with differences in contact size and anteriority for [c]. Other arguments in favor of the articulation-based hypothesis will be adduced next.

1.2.1. Stop burst frication

A problem with an interpretation of velar softening based on acoustic equivalence is that this process appears to have affected not only aspirated voiceless stops with long and salient releases composed of frication and aspiration (e.g., in the Germanic languages), but also shorter and less perceptible unaspirated voiceless stop releases (e.g., in Romance). Analysis data show that word initial VOT values are clearly shorter for unaspirated /k/ (e.g., 29 ms in Puerto Rican Spanish; Lisker & Abramson, 1964) than for aspirated /k/ (e.g., 74 ms in English; Zue, 1980). This large VOT duration difference appears to be associated primarily with aspiration though in practice it is hard to separate aspiration from local frication since the two events overlap with each other (Hanson & Stevens, 2003). The frication noise is typically longer for affricates than for stops (Ladefoged & Maddieson, 1996, p. 90), much more so if stops are unaspirated. Data for /tʃ/ in Spanish and Italian indicate indeed that the fricative portion of the affricate is about 80 ms in slow speech and 65 ms in fast speech, which is much longer than the VOT values for unaspirated stops (Maddieson, 1980).

Differences in burst acoustic prominence between unaspirated and aspirated stops should render the perceptual confusion between front /k/ and /tʃ/ more unlikely for the former class of stop consonants than for the latter. Informal listening of CV excerpts taken from Catalan meaningful sentences reveal, indeed, that unaspirated front velar stop bursts are not confusable with /tʃ/. This observation is consistent with Guion's finding that aspirated front velar stops are harder to be confused with /tʃ/ when burst frication is shortened (Guion, 1998), and suggests that a noticeable increase in burst frication duration and/or intensity is needed for an unaspirated front velar stop to yield an affricate percept.

The little acoustic salience of the burst for voiced unaspirated stops renders the acoustic equivalence explanation even less feasible in case that velar softening is associated with front /g/, e.g., /g/ > /dʒ/ as in Catalan [dʒɛl] gel from Latin /ˈgɛlo/ GELU 'ice'.

1.2.2. Velar palatalization and velar softening in other contexts and positions

Velar softening may also take place in contexts and positions where /k, g/ are usually back rather than front. In Gallo-Romance, velar softening was implemented through a second palatalization wave dated about the 5–7th centuries A.D. and even later, and operating not only before front vocalic segments but also before /a/ and also /ə/ as well as in word final position (French [ʃɛvʀ] chèvre CAPRA 'goat', [ʃaʀbɔ̃] charbon CARBONE 'coal', Rhaetoromance [satʃ], [satç], [saç] SACCU 'sack'; Goebl, 1998, map 678; Pope, 1934, p. 128). This change appears to be at odds with the acoustic equivalence hypothesis since the spectral burst for back /k/ exhibits a much lower frequency than the /tʃ/ frication noise, i.e., it is located about 1600–1800 Hz before /a/ and about 750–1100 Hz before back rounded vowels (Zygis et al., 2008; Zue, 1980).

In support of the articulation-based hypothesis, the (alveolo)palatal stop realization [c] of unaspirated /k/ may occur in those same conditions in languages and dialects of the Gallo-Romance family. This is the case for the Rhaetoromance dialects Romansh, Ladin and Friulian ([can] CANE 'dog', [caw] CAPUT 'head'; Brunner, 1963; Haiman & Benincà, 1992, pp. 66–70; Lutta, 1923, p. 40) and for Northern Italian dialects ([car] CARU 'dear', [sac] SACCU 'sack'; Rohlfs, 1966; Salvioni, 1901). Moreover, (alveolo)palatal stops and affricates may cooccur before /a/ and word finally in the dialectal areas referred to, e.g., Rhaetoromance [ˈcawɾa], [ˈtʃawɾa] CAPRA 'goat', [rɛc], [rɛtʃ], [rəts] REGE 'king' (Jaberg & Jud, 1928–1935, map 1079; Luzi, 1904, p. 769). Velar palatalization has taken place in the same circumstances in the Majorcan Catalan dialect under analysis in the present paper (Recasens, 1996, pp. 243–244), as well as in other language families, e.g., in Alsean in the Northwest coast of America where [c] occurs before /a/ and /ə/ and word finally (Buckley, unpublished (a)), and in Persian where word final /k/ is realized [c] ([xac] 'earth'; Bhat, 1974, p. 46; Buckley, unpublished (b)).

The acoustic equivalence hypothesis would be compatible with an especially anterior, [ɛ]-like realization of /a/. It has been argued that this realization must have existed in Gallo-Romance at the time velar softening applied, based mostly on the fact that /a/ has yielded a mid front vowel in open syllables in languages such as French (e.g., mer MARE, the example chèvre above; Buckley, unpublished (b)). It is by no means clear, however, whether /a/ raising preceded or followed the generation of the outcomes [c] or [tʃ] of /k/. Progressive palatalization of /a/ by a preceding (alveolo)palatal consonant is a common phenomenon (Valencian Catalan [ʎɛrk] llarg LARGU 'long'; Recasens, 1996, p. 101), and may operate in parallel to progressive /j/ insertion as exemplified by Old French chier derived from Latin CARU 'dear' (Lausberg, 1970, pp. 261–262; Pope, 1934, pp. 127–128, 163). Moreover, the vowel /a/ has stayed unchanged in several Romance domains where /ka/ has evolved into [ca], [tʃa] or [tsa] (i.e., in those mentioned above as well as in Northern Occitan and Francoprovençal), and velar palatalization before an unfronted variant of /a/ occurs in present-day Northern French (see Coustenoble, 1945, p. 77 and palatographic material in Rousselot, 1924–1925, p. 607). It is also the case that velar softening in French operated before the diphthong /aw/ where an [ɛ]-like realization of /a/ is problematic (e.g., chose CAUSA 'thing', where o was issued from /aw/ through monophthongization). Another point to be made is that the spectral peak for /k/ before /ɛ/ falls between 2000 and 2500 Hz and thus, below that for /tʃ/ (Zygis et al., 2008; Zue, 1980), and that velar softening applies less frequently before /ɛ/ than before the higher cognates /i, e/ in the world's languages (Bhat, 1974, p. 30).

1.2.3. Supplementary evidence

As shown in the preceding sections, evidence in support of the articulation-based hypothesis derives from the observation that the (alveolo)palatal stop and the outcoming affricate may share an analogous closure placement in velar softening processes. Voicing, prosodic and lexical characteristics may also play a role. Thus, the affricate or fricative outcomes may be more anterior for original /k/ than for original /ɡ/ (French [sɑ̃] cent CENTU 'one hundred', [ʒɑ̃] gens GENTE 'people'), as well as word initially than intervocalically (Ladin ['tsento] CENTU 'one hundred', [ve'tʃin] VICINU 'neighbour'; Gartner, 1910, p. 189) and in stressed than unstressed syllables (Friulian ['tʃazɛ] CASA 'house', [ka'miŋ] CAMINU 'path'; Jaberg & Jud, 1928–1935, map 269). All these cases may be accounted for assuming that tongue contact size and closure fronting, as well as duration, are greater for voiceless stops than for voiced stops and increase with stress and at the edges of the lexical and prosodic domains (Cho, 2001; Farnetani, 1990; Fougeron, 2001; Fougeron & Keating, 1997; Keating, Wright, & Zhang, 1999).

Another finding more in support of the articulation-based hypothesis than of the acoustic equivalence hypothesis appears to be the alveolar affricate outcome /ts/ of velar softening. Assuming that the alveolar affricate has been issued directly from a stop, it is hard to envisage how a front velar stop burst may be confused perceptually with the sharp /s/ frication noise exhibiting a spectral peak well above the typical 2500–3500 Hz frequency for front /k/. In principle, the articulation-based hypothesis could handle better this sound replacement, as revealed by articulatory data showing that very front (alveolo)palatal stops may be articulated at the alveolar zone and, therefore, at the same place of articulation as /ts/ (Section 1.1.1).

1.3. Velar palatalization mechanisms

In the light of the data described above, velar palatalization should not be treated simply as an assimilation through which /k/ acquires the palatal place of articulation of a following front vocalic segment. We would like to suggest instead that the change /k/>[c] may be achieved through two production mechanisms, i.e., gestural blending and gestural strengthening.

Front velar palatalization in the adjacency of a dorsopalatal vowel or glide is achieved through gestural blending since both the consonant and the vocalic segment are produced with the same tongue dorsum articulator in this case. Blending may be implemented through two different production strategies. It may yield an intermediate articulation between the stop and the front vowel or glide, as for postpalatal realizations of /k/ before a front vocalic segment (Browman & Goldstein, 1989, 1992). Another option is for blending to give rise to an articulation encompassing or exceeding the combined closure or constriction areas of the two consecutive phonetic segments, as for several Catalan clusters made up of /t, n/ and the alveolopalatals /ʎ, ɲ/ (Recasens, 2006). The latter mechanism could account for why front velar stops may exhibit so much closure fronting when implemented as (alveolo)palatal stops.

Specific conditions upon which velar palatalization occurs suggest that gestural strengthening may also act as a velar palatalization trigger (Straka, 1965). This suggestion is valid for the word initial and word final positions and for stressed syllables which favor lengthening and an increase in tongue contact in the consonant, as well as before open vowels where (alveolo)palatal closure formation requires much tongue dorsum raising. In view of the descriptive materials adduced in Section 1.2.2, it looks feasible to claim that velar palatalization through strengthening may apply across the board except word internally before /ɔ, o, u/ perhaps since keeping a very posterior closure location and the lips relatively rounded and protuded in anticipation to a back rounded vowel renders tongue dorsum raising towards the palate especially hard.

Diachronic evidence in support of these two velar palatalization mechanisms comes from Romance where velar softening occurred twice in two different sets of conditions: only before front vocalic segments in Late

Latin and in practically all early Romance languages presumably through velar palatalization induced by gestural blending (see Section 1.1); before other vowels and word finally in a subset of Romance languages and dialects a few centuries later, presumably through velar palatalization induced by gestural strengthening (see Section 1.2.2).

1.4. Research goal

The goal of the present study is to test the articulation-based hypothesis by looking for the acoustic cues which could contribute to the generation of affricates from (alveolo)palatal stops, and by speculating on the perceptual effectiveness of those cues. Articulatory data will be adduced in order to substantiate the claim that velar palatalization and velar softening may apply not only before front vocalic segments but also in other conditions allowing an increase in linguopalatal contact fronting to occur.

Acoustic analyses and perceptual tests will be carried out on the same electropalatographic (EPG) data for Majorcan Catalan used in Recasens and Espinosa (2006), i.e., on productions of unaspirated /k/ next to /i, a, u/ in word/utterance initial, intervocalic and word/utterance final position. The main reason for selecting Majorcan Catalan is because this dialect has the (alveolo)palatal stop [c] in its sound inventory, which was probably issued as an internal development and has been reported to sound [tʃ]-like sporadically (Bibiloni, 1983). Descriptive and experimental studies indicate indeed that, in Majorcan, [c] is an allophone of /k/ appearing most typically before a front vowel but also before /a/ and /ə/ and word finally after any vowel but not word internally before a back rounded vowel ([ci] <u>qui</u> 'who', ['cazə] <u>casa</u> 'house', [sac] <u>sac</u> 'sack', but [kus] <u>cus</u> 'he/she sows'; Recasens & Espinosa, 2006; Veny, 1983). This scenario differs from that for the other Catalan dialects such as Eastern Catalan where /k/ may be slightly more anterior or more posterior depending on the following vowel (see Section 1.1).

The chances that (alveolo)palatal [c] may be categorized as /tʃ/ should depend on the following predictions about the spectral peak frequency, intensity and duration of the stop burst, and the endpoint and range of the vowel formant transitions.

As for the burst spectral frequency, [c] should show a 3000–4000 Hz front-cavity-dependent spectral peak appropriate for or similar to that for /tʃ/ (Keating & Lahiri, 1993). Vowel environment is expected not to affect these spectral characteristics much since (alveolo)palatals should coarticulate little with the contextual vowels (Recasens, 1984). Given that stop bursts and affricate noises differ in intensity and duration, these two parameters ought to be less favorable to velar softening than spectral frequency: the intensity of the frication noise increases with airflow volume velocity and the cross-sectional area of the constriction (Stevens, 1998) and, therefore, is higher for affricates than for unaspirated stops; moreover, affricate frication noises are longer than unaspirated stop bursts (see Section 1.2.1). In specific circumstances, however, the intensity level and duration of the [c] burst may approach those for /tʃ/. Indeed, the stop burst intensity is also determined by front-cavity size at stop release and, thus, should be especially high before low and back vowels which are articulated with a larger front cavity than front vowels (Dorman, Studdert-Kennedy, & Raphael, 1977). This observation is consistent with data for the Australian languages showing that (alveolo)palatal stops combine better with back vowels than with front vowels, i.e., /#ca/ and /#cu/ are preferred to /#ci/ (Butcher, 2004). As for duration, VOT data reported in the literature (Docherty, 1992, pp. 26–27) indicate that bursts may be longer before high vs. low vowels. Burst duration may also be an effective velar softening cue word finally where /k/ may give rise to affricate and fricative realizations (see evidence from Rhaetoromance in Section 1.2.2). Since Catalan and other Romance languages do not have a spirantization rule affecting voiceless stops, the replacement of [c] by [ç] in word final position is prone to be caused by prepausal lengthening of the stop burst frication period rather than by shortening or elimination of the stop closing phase.

Regarding the vowel transitions, the acoustic theory of speech production predicts that fronting closure location from the postpalate and mediopalate towards the alveolo-palatal zone should cause the endpoint frequency of the F2 vowel transitions to lower slightly or stay the same, and the endpoint frequency of the F3 vowel transitions to rise (Fant, 1960; Ladefoged & Bladon, 1982). The rationale for these formant frequency variations is to be sought in the fact that F2 for (alveolo)palatals is a half-wavelength resonance of the back cavity and is positively associated with the tongue pass rather than with the lip section, while F3 is inversely related to front-cavity length (Fant, 1960; Stevens, 1998). Unpublished data on Eastern Catalan /tʃ/ (referred to partly in Recasens, 1986) reveal that, for the vowel formant transitions for [c] to approach those for the affricate consonant, the F2 transition endpoints should occur at about 2000–2100 Hz (in the context of /i, e, ɛ/), 1800 Hz (/a, ə/), 1700 Hz (/ɔ, o/) and 1550 Hz (/u/), while the F3 transition endpoints should take place at about 2700–2900 Hz (/i, e, ɛ, a, ə/) and 2400–2600 Hz (/ɔ, o, u/). These formant frequency values are highly similar to those for other (alveolo)palatal consonants though slightly lower in the case of F2 and slightly higher in the case of F3 (Recasens, 1984).

The frequency extent of the formant transitions (i.e., the formant frequency range) varies with vowel context in a similar way for all consonants produced at the palatal and alveolopalatal zones. In view of the formant transition endpoints just mentioned, the F2 frequency range should be greater for low and back vowels and ought to increase as front vowels become lower. Vowel intensity, which increases with oral opening and is thus greater for /a/ than for /i, u/, ought to contribute to the prominence of the vowel transitions as well (English: Lehiste and Peterson, 1959; Eastern Catalan: Recasens, 1986). A possible road to velar softening may be the integration of long-range and intense formant transitions in CV sequences with [c] as the glide [j], followed by the perception of [j] as /ʃ/ whenever an increase in the degree of lingual constriction at stop release causes much frication to occur. Present-day phonetic variants and written forms in documents from the past suggest that the change /k/ > /tʃ/ before /a/ may have developed indeed through a transitional glide, which was inserted in Old French (see Section 1.2.2) and may still be heard in Francoprovençal ([tʃjɛ(r)] cher CARU 'dear'; Gauchat, Jeanjaquet, & Tappolet, 1925, p. 60) and Wallon and Picard ([k(j)ɛr], [cjɛr], [tʃ(j)ɛr] cher CARU 'dear', [tje], [cjɛ], [tʃ(j)ẽ] chien CANE 'dog', [dʒjãb] jambe CAMBA 'leg'; Bruneau, 1913, p. 410; Carton, 1972, p. 454; Haust, 1953–1997, pp. 106, 109).

In summary, the identification of (alveolo)palatal [c] with /tʃ/ and thus, the articulation-based hypothesis of velar softening, is expected to work out mostly for the frequency component of the burst and the formant transition endpoints largely irrespective of vowel context and position. Burst intensity and formant transition ranges are expected to favor velar softening mostly before low and back vowels, and burst duration could give rise to a /tʃ/ percept most easily before high vowels and to an affricate or a fricative word finally. The effectiveness of all these parameters is subjected to the presence of a prominent burst frication noise which is associated with a narrow constriction and a high airflow volume at stop release.

Section 2 of the present article tests these predictions on the best candidates for velar softening through an analysis of the articulatory and acoustic characteristics of the (alveolo)palatal and velar allophones of /k/ in Majorcan. Section 3 reports results from a series of perception experiments where (alveolo)palatal and velar realizations of /k/ differing articulatorily and acoustically were presented to Catalan listeners for identification.

2. Experiment I (production)

2.1. Method

2.1.1. Recording procedures

Data subjected to recording and analysis correspond to five repetitions of the meaningful Catalan sentences presented in Table 1 where /k/ carries lexical stress and occurs word/utterance initially, word/utterance finally and in symmetrical intervocalic sequences with the vowels /i, a, u/. The intervocalic velar stop consonant is word initial when combined with /i, a/ (V#CV) but word final when combined with /u/ (VC#V). This difference was introduced so as to allow for a maximal degree of palatalization before /u/ in view of the fact that, in Majorcan, /k/ is realized as [c] word finally but as [k] before any back rounded vowel word medially (see Section 1.4). In order to compare the phonetic properties of the (alveolo)palatal realization of /k/ with those of /tʃ/, EPG and acoustic data for the affricate in the word ['ratʃə] ratxa embedded in seven repetitions of the sentence té una ratxa bona 'he/she has a stroke of luck' were also recorded.

Table 1
Catalan sentences of the reading list with the target sequences underlined.

/#ki/	*qui arribarà*	'who will arrive?'
/#ka/	*casa còmoda*	'comfortable house'
/#ku/	*cus força*	'he/she sews a lot'
/iki/	*en repartí quinze*	'he/she distributed fifteen items'
/aka/	*ell no hi va caure*	'he/she did not realize'
/uku/	*treu el suc últim*	'he/she extracts juice from it'
/ik#/	*l'avi és molt ric*	'grandfather is very rich'
/ak#/	*omple el sac*	'fill the sack'
/uk#/	*n'hi treu el suc*	'take out the last juice'

Recordings were performed by the five male speakers of Majorcan Catalan AR, BM, MJ, ND and CG. Linguopalatal contact configurations were gathered every 10 ms with the Reading EPG-3 system using wedge-shaped artificial palates about 1.5 mm thick equipped with 62 electrodes. In order to reduce the interference of the plates with the speakers' speech, all five speakers were asked to wear the artificial palates for an acclimatization period of about 2 h before the recordings (Hardcastle, Jones, & Knight, 1989). The recorded material was judged to be highly acceptable regarding intelligibility and naturalness.

The acoustic signals were digitized at 10 kHz and processed with the Computerized Speech Lab (CSL) analysis system of Kay Elemetrics using the same temporal resolution as the EPG signal. While the sampling rate of the EPG-3 system may seem rather low, the fact is that the most relevant frequency information for stop bursts is found below 5 kHz (Stevens, 1998), and that other studies have used the same sampling rate for the acoustic analysis of stop bursts (Keating & Lahiri, 1993) and for the preparation of stop burst stimuli for perceptual place identification (Repp & Lin, 1989). The spectral peak for the /tʃ/ frication period also lies below that frequency.

2.1.2. Articulatory measurements

Closure location for the stop and for /tʃ/ was determined at three temporal points, at closure onset and offset (i.e., at onset and offset of complete activation of all electrodes at one or more rows of the artificial palate) and at the point of maximum contact or PMC (i.e., at the frame showing the highest number of on-electrodes over the entire palate surface). As shown in the upper right linguopalatal contact configuration in Fig. 1, the artificial palate is equipped with eight rows of electrodes extending from frontmost row 1 at the top through backmost row 8 at the bottom, which may be grouped into several articulatory zones for data interpretation: front alveolar (at the two front rows), postalveolar (at rows 3 and 4), prepalatal (at rows 5 and 6), mediopalatal (at row 7), postpalatal (at row 8). The linguopalatal contact representations of the figure are normalized for contact placement and, therefore, allow

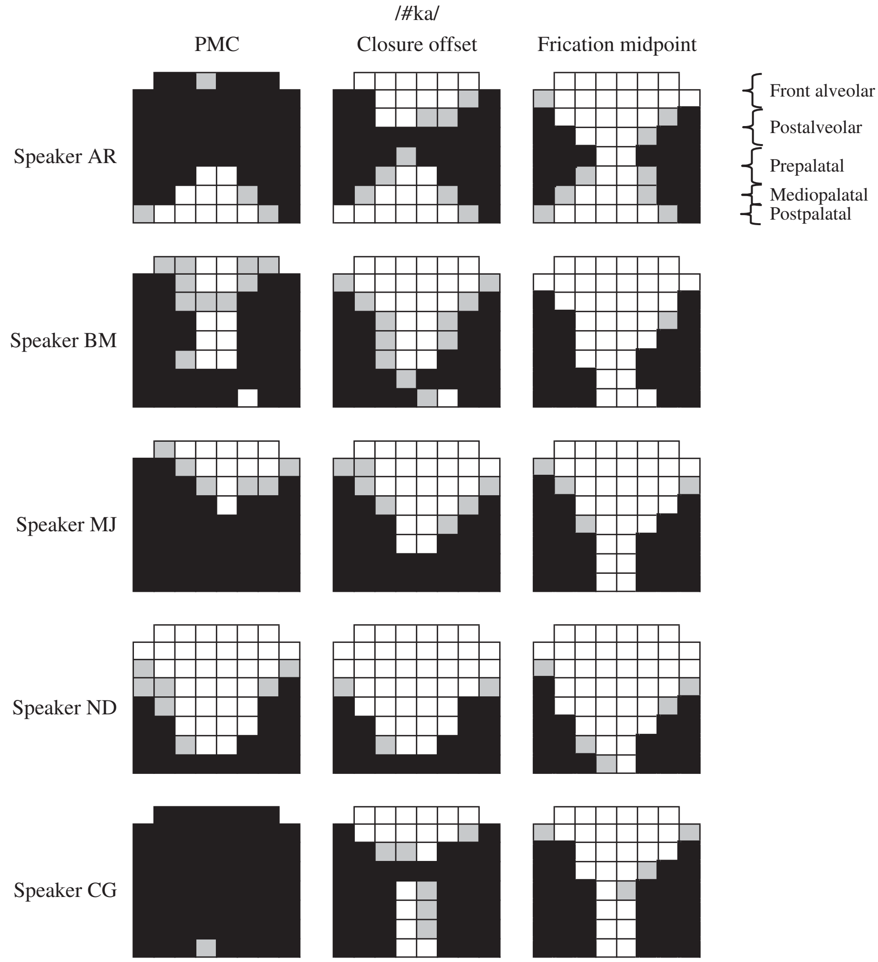

Fig. 1. Linguopalatal contact configurations for word/utterance initial /#ka/ at point of maximum contact or PMC, closure offset and frication midpoint for all Majorcan Catalan speakers. The correspondence between rows of electrodes and articulatory zones is given at the top right EPG pattern. Electrodes have been assigned different colour shades depending on frequency of activation across tokens, i.e., black (80–100%), grey (40–80%) and white (0–40%).

drawing cross-speaker comparisons in place of articulation independently of speaker-dependent differences in palate size and shape.

The articulatory analysis involved the calculation of a contact anteriority index (CA) and an overall contact index (Q) over the whole linguopalatal contact surface. Measurements were taken at PMC for each sequence, token and speaker. The index Q is the percent of contacted electrodes out of the total amount of 62 electrodes of the artificial palate. The index CA is an indicator of the degree of closure fronting and was measured applying the following formula (Fontdevila, Pallarès, & Recasens, 1994):

$$\begin{aligned}\mathrm{CA} = {} & [\log[[1(R_8/8) + 9(R_7/8) + 81(R_6/8) \\ & + 729(R_5/8) + 6561(R_4/8) + 59{,}049 \\ & (R_3 + 8) + 531{,}441(R_2/8) \\ & + 3{,}587{,}227(R_1/6)] + 1]]/[\log(4{,}185{,}098 + 1)].\end{aligned}$$

In the ratios within parentheses, the number of contacted electrodes on a given row (i.e., R8, R7, etc.) is divided by the total number of electrodes on that row. Each ratio is multiplied by a coefficient number. These coefficients are chosen so that the activation of all electrodes at and behind a specific row always yields a lower index value than the activation of a single electrode at more anterior rows.

2.1.3. *Acoustic measurements*

Acoustic analysis involves measuring the spectral peak, acoustic energy and duration of the stop burst and of the affricate frication period, and the frequency endpoints and ranges of the F2 and F3 vowel transitions, for both /k/ and /tʃ/. Frication spectral peaks were identified on autocorrelation LPC spectra with a 25 ms full-Hamming window and 14 coefficients. In the case of /k/, spectra were obtained at the onset of the frication noise immediately after the burst spike, which was located just after closure offset on the EPG record or had to be determined visually on spectrographic displays if showing up later in time (see also Keating & Lahiri, 1993). In a few instances where the stop burst exhibited two spikes, frication onset was taken to occur between the two if they were close to each other and after the second spike if they were far apart. In the case of affricates, spectral measures were taken at the midpoint of the frication period.

Spectra were displayed on a 0–80 dB scale and averaged across repetitions of each sequence for each speaker. The productions of the velar stop phoneme were categorized as [k] or [c] based on the allophonic distribution of /k/ in Majorcan Catalan (see Section 1.4) and on inspection of the EPG linguopalatal contact configurations. Their burst spectral peak was identified and measured according to well-established criteria (Blumstein, 1986; Fant, 1960; Keating & Lahiri, 1993): purely velar realizations of /k/ should show a peak at about 1500–2000 Hz in the context of /a/ and at about 1000 Hz or lower in the context of /u/; postpalatal or postpalato-velar realizations of /k/ in the context of /i/ ought to have a 2500–3000 Hz burst spectral peak; bursts for the (alveolo)palatal stop [c] ought to exhibit frequency peaks at 3500–4000 Hz or higher in front and low vowel contexts and at about 2000–3000 Hz before /u/.

In the absence of a well-defined spectral peak, spectral frequency measurements were taken at the midpoint of a plateau or amplitude maximum extending over a certain frequency range. A requirement for a well-formed plateau was that it did not include more than two nearby spectral peaks of comparable amplitude within the expected frequency range, and that the amplitude of the spectral valley between the two peaks did not exceed 5% of the overall signal amplitude for a given speaker. Spectral peaks and plateaus are exemplified in Fig. 2. Mean spectral contours in the figure show a plateau with a frequency midpoint at 3359 Hz for /#ki/ and a well-defined spectral peak at 2500 Hz for /#ka/. Taking peak frequency measurements on mean spectral displays across tokens of each sequence instead of on spectral displays for the individual tokens avoided facing a good number of cases where measurements were uncertain because the amplitude maxima were plateaus instead of peaks.

Absolute energy values for the frication period of stop bursts and affricates were measured for each sequence token at the same temporal frame selected for measuring the front-dependent cavity spectral frequency peak. Energy values in dB are obtained by multiplying intensity by duration (Dorman et al., 1977). Relative energy values were also calculated for all sequence repetitions by dividing the absolute energy value at the stop burst or affricate frication period by that at the midpoint of the vowel (Cho, Jun, & Ladefoged, 2002). For stops, vowel energy was measured at the stressed vowel following the consonant in #CV and VCV sequences or preceding the consonant in VC# sequences. For the affricate, the vowel showing the highest energy was chosen for the relative energy calculation, i.e., V2 = [ə] for speakers AR and MJ and V1 = [a] for speakers BM, ND and CG. In all cases, dB readings were computed on 10 ms window energy profiles which included a portion of the consonant and the adjacent vowel.

The duration of the stop bursts was taken to occur from closure offset at the burst spike until the first glottal pulse of the following vowel in #CV and VCV sequences, or until burst frication offset in VC# sequences. The duration of the frication period for affricates was measured from closure offset where burst and frication begin to frication offset, simultaneously on EPG and spectrographic displays.

Formant frequency readings for the vowel transitions were carried out for all tokens of each sequence in 10 ms steps. Measurements were taken on spectrographic displays placing a cursor in the middle of the formants with the assistance of LPC spectra whenever it was felt that the spectrographic readings were not reliable enough. F2 and F3 transition endpoints were measured at vowel onset for

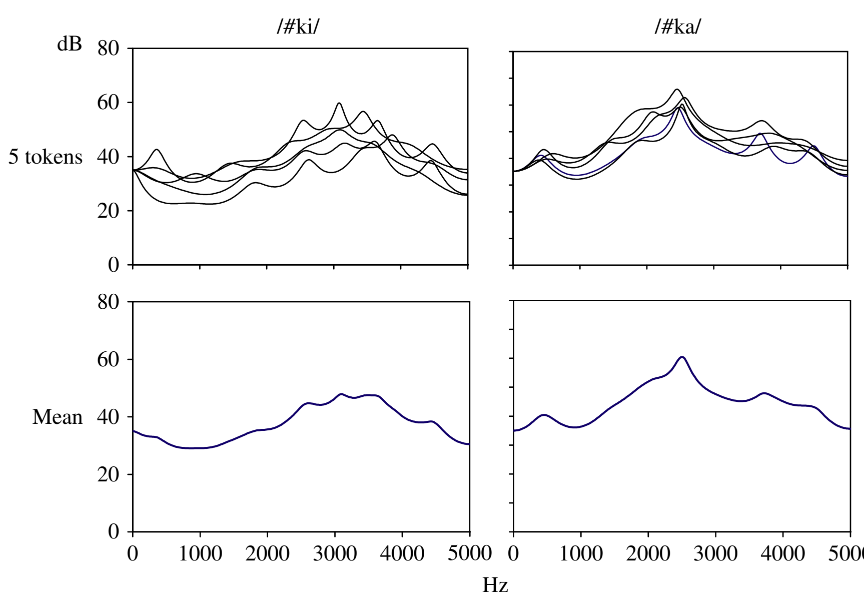

Fig. 2. Burst spectral contours for five repetitions of /#ki/ (top left) and /#ka/ (top right) according to speakers MJ and ND, respectively, and corresponding mean contours across repetitions (bottom). Amplitude maxima occur at a plateau in the bottom left spectral configuration and at a peak in the bottom right one.

#CV sequences and for the CV portion of VCV sequences ((V)CV condition), and at vowel offset for VC# sequences and for the VC portion of VCV sequences (VC(V) condition). We also computed the frequency ranges of the vowel formant transitions by subtracting the frequency value at a given transition endpoint from that obtained at the corresponding vowel midpoint. Thus, for example, the range of the F2 transition for /ki/ in the sequence /iki/ amounts to the difference between the F2 frequency at V2 = /i/ onset and at V2 = /i/ midpoint, and that for /ik/ in the same VCV sequence to the difference between the F2 frequency at V1 = /i/ offset and at V1 = /i/ midpoint. Ranges may be positive or negative depending on whether the frequency at the transition endpoint is higher or lower than that at the vowel midpoint.

Table 2
Distances in mm between the frontmost row 1 and each of the remaining seven rows of electrodes of the artificial palate (e.g., R1–R2, R1–R3, etc.) for the Majorcan speakers AR, BM, MJ and CG. Data for speaker ND are only given for the distance R1–R8 since closure for this speaker takes place invariably at or behind row 8.

	AR	BM	MJ	CG	ND
R1–R2	4	3.5	3.5	3.5	
R1–R3	7.5	6.5	7	8	
R1–R4	11	9.5	10.5	12.5	
R1–R5	17.5	15.5	18	18.5	
R1–R6	24.5	22.5	25.5	25.5	
R1–R7	32	28.5	33	32	
R1–R8	41.5	35.5	40	39.5	45

2.1.4. *Articulatory–acoustic correlations*

The relationship between front-cavity length, and the spectral peak frequency and the energy level of the stop burst, was also analyzed.

It was hypothesized that fronting closure location for the stop would cause the frequency of the burst spectral peak to increase and thus, to approach that for the frication component of /tʃ/, and the burst energy level to decrease thus becoming less /tʃ/-like (see Section 1.4). Front-cavity length was estimated on average contact patterns of /k/ across tokens of each sequence for each speaker and at two moments in time, i.e., at PMC where the consonant is supposed to exhibit its target articulatory configuration, and at closure offset just before the stop burst which ought to be the most effective velar softening acoustic cue. It was taken to equal the distance between row 1 of the artificial palate and the frontmost row of electrodes showing maximal activation at closure location. In order to calculate this distance, the intervals between row 1 of electrodes and each of the seven remaining rows were measured from projections of each speaker's artificial palate on a flat surface (see Table 2). The frontmost row at closure location was identified with the row exhibiting 80–100% activation of all electrodes, or else 40–80% activation of one or the two centralmost electrodes and 80–100% activation of the remaining electrodes. Frontmost closure location was taken to occur at row 8 or behind it whenever all electrodes except for the two central ones on this row were contacted more than 80% of the time and central contact activation at rows 1–7 was less than 40%. No measures of lip rounding were obtained which would have rendered estimates of front-cavity length for the sequences /#ku/ and /uku/ more realistic. Burst spectral peak frequency and energy data were correlated with closure location values instead of with CA or contact anteriority index values since the latter measure is sensitive to the activation of any electrodes placed before closure location and therefore, may fail to reflect the consonant place of articulation.

2.1.5. *Statistics*

In order to ascertain the contribution of each potential articulatory and acoustic cue to the identification of /k/ as /tʃ/, ANOVAs with repeated measures were run with the SPSS 15 statistical package on data for the ten parameters CA or contact anteriority index, *Q* or overall contact index, burst spectral peak, burst absolute energy, burst relative energy, burst duration and the endpoints and ranges of the F2 and F3 vowel transitions. The alveolopalatal but not the postpalatal or (postpalato)velar realizations of speaker CG's productions of /k/ in the sequences /aka, ak#, uk#/ were included in the statistical tests (see Section 2.2.1.1).

There were two within-subject factors in the RM ANOVAs, i.e., 'vowel' ('/i/', '/a/', '/u/') and 'position' ('initial', 'intervocalic', 'final'). For the analysis of the F2 and F3 vowel transitions data, the 'intervocalic' position level was split into the two levels 'VC(V)' and '(V)CV'. Each of the five Majorcan speakers contributed one averaged score per condition (Max & Onghena, 1999). Huynh–Feldt corrected degrees of freedom were applied to the main effects and interactions whenever the sphericity requirement was not fulfilled, and Bonferroni post-hoc tests were run on the significant main effects involving more than two levels of an independent variable. The degree of significance was set at $p<0.05$. Significant interactions were interpreted on the basis of results obtained from additional RM ANOVAs performed independently on data for each vowel and position.

A principal component analysis (PCA) was also carried out in order to identify unobserved bundles of phonetic parameters signalling velar palatalization (and presumably velar softening) as well as the relative contribution of these parameters within each bundle. Factors were computed according to Kaiser's criterion, i.e., only factors with an Eigenvalue exceeding 1 were retained. PCA was performed on data across repetitions and speakers using the same ten parameters tested using ANOVAs.

2.2. *Results*

Section 2.2 is structured as follows. First, we provide the individual articulatory and acoustic characteristics for the (alveolo)palatal stop realizations of /k/ in Majorcan, and investigate the extent to which those characteristics match the ones for /tʃ/ and, therefore, may cue velar softening in perception. In the light of results from the principal component analysis, we then study whether the articulatory and acoustic properties of interest could act jointly in the perceptual categorization of (alveolo)palatal stops as /tʃ/. In all cases, the role of vowel context and word position will be evaluated.

2.2.1. Individual phonetic properties

2.2.1.1. Closure location for /k/. Fig. 3 presents differences in closure location for /k/ at PMC as a function of vowel context, position and speaker. Lines indicating closure location and extent have been assigned to rows showing more than 80% electrode activation even if their two centralmost electrodes did not achieve this contact percentage. Variations in linguopalatal contact occur at the front closure border which accounts for why CA or contact anteriority index and *Q* or overall contact index are highly correlated (see Section 2.2.2).

Data in the figure have been subdivided into three groups according to place of articulation: postalveolar or postalveolo-prepalatal for speaker AR (top panel); purely palatal for speakers BM, MJ and ND, and somewhat more anterior for the two former speakers than for the latter (middle panel); essentially alveolopalatal with a great deal of contact all over the alveolar and palatal zones for speaker CG (bottom panel). In comparison to other languages and dialects where velars stay velar, /k/ in Majorcan undergoes a shift in place of articulation from velar (i.e., postpalatal or postpalato-velar in the case of front velars, velar proper for back velars) to (alveolo) palatal. Judging from the EPG data, this is the case for all speakers except partly for speaker ND where the change of interest applies to back velars only.

Statistical results yielded a main effect of 'vowel' ($F(2,8) = 15.12$, $p = 0.002$ for CA; $F(2,8) = 9.51$, $p = 0.008$ for *Q*), no main effect of 'position', and a 'vowel' $\times$ 'position' interaction ($F(4,16) = 32.17$, $p = 0.000$ for CA; $F(4,16) = 21.21$, $p = 0.000$ for *Q*). As shown by mean values in Fig. 4, significant effects are mainly associated with a larger and more anterior degree of tongue contact for /k/ in the context of /i, a/ than of /u/ in word/utterance initial position. Fig. 3 reveals that the absence of contact for word/utterance initial /k/ before /u/ is indicative of a velar place of articulation behind row 8 for all speakers (better postpalato-velar for speaker AR). The 'vowel' $\times$ 'position' interaction is also associated with higher CA and *Q* values word/utterance initially than intervocalically and word/utterance finally in the /i/ and /a/ context conditions, which may be ascribed to initial strengthening (see Fig. 4). Fig. 3 shows indeed that /#ki/ and /#ka/ may be produced with more anterior tongue contact than /iki, ik#/ and /aka, ak#/ for most speakers. Judging from these findings, it may be concluded that velar palatalization may operate almost

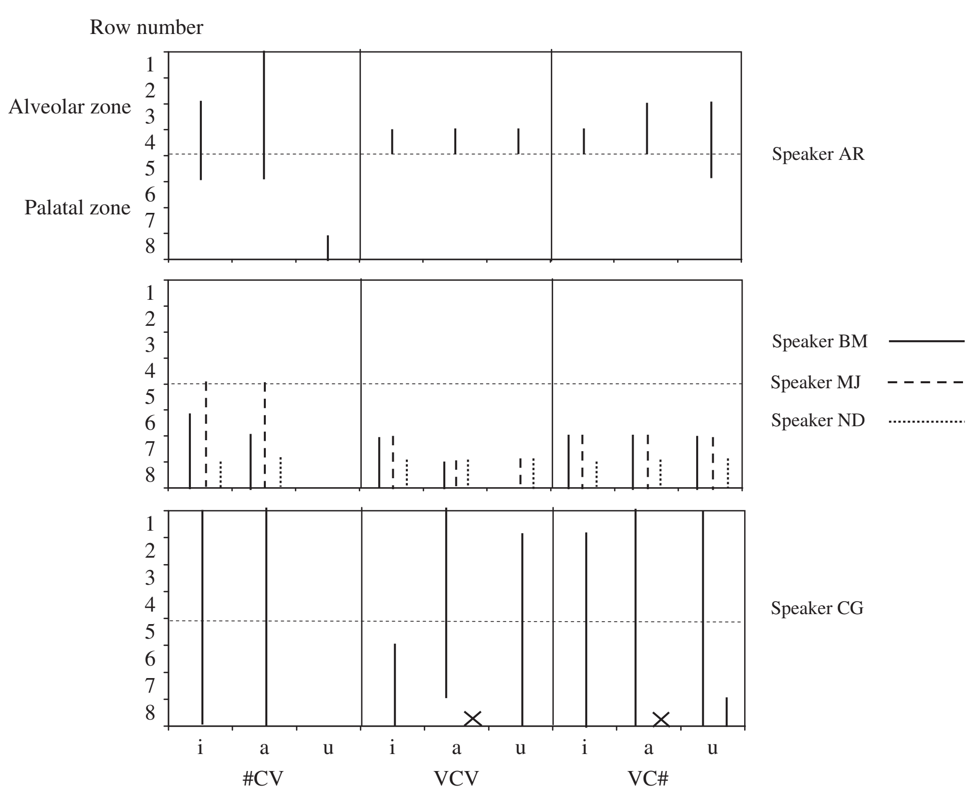

Fig. 3. Closure location for /k/ as a function of vowel context and position for all speakers. Lines indicate closure placement and extent, and crosses co-occurring with lines the absence of closure and thus, a velar realization. The correspondence between rows of electrodes and articulatory zones is given along the vertical axis.

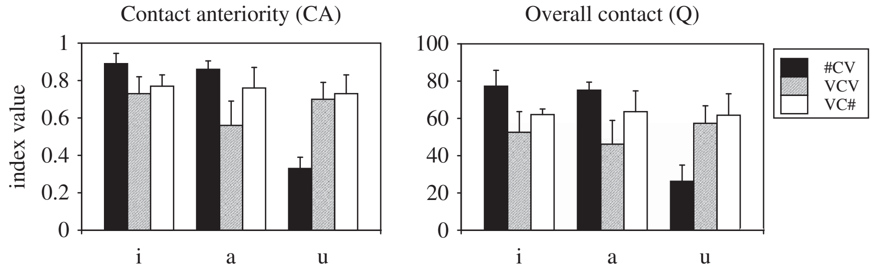

Fig. 4. Cross-speaker mean contact anteriority index (CA) and overall palatal contact index (Q) values and standard deviations for word/utterance initial, intervocalic and word/utterance final /k/ in the context of /i, a, u/.

in any position and vowel context except word/utterance initially before /u/, and most especially in word/utterance initial position before /i, a/.

Speaker CG's productions of /k/ in the sequences /aka, ak#, uk#/ were alveolopalatal 60–80% of the time and much less often either velar or postpalatal or postpalatovelar (see Fig. 3). The alveolopalatal variety will be given priority in the present study since, in addition to being the majoritary realization, it conforms to the distribution of the allophones [c] and [k] of /k/ in Majorcan referred to in Section 1.4.

2.2.1.2. Comparison between /k/ and /tʃ/. As shown by the linguopalatal contact configurations represented in Fig. 5, closure location for the affricate occurs mostly at the centroalveolar or postalveolar zone at PMC, and becomes more retracted as closure offset is approached in the case of speakers BM and ND. Gradual retraction in adjustment for frication during the second half of the affricate closure period has been reported to occur for /tʃ/ in other languages (English: Mair, Scully, & Shadle, 1996). Constriction location at the midpoint of the /tʃ/ frication period is analogous to that occurring at closure offset in the case of speakers AR and MJ and extends over the postalveolar and palatal zones in the case of the remaining speakers.

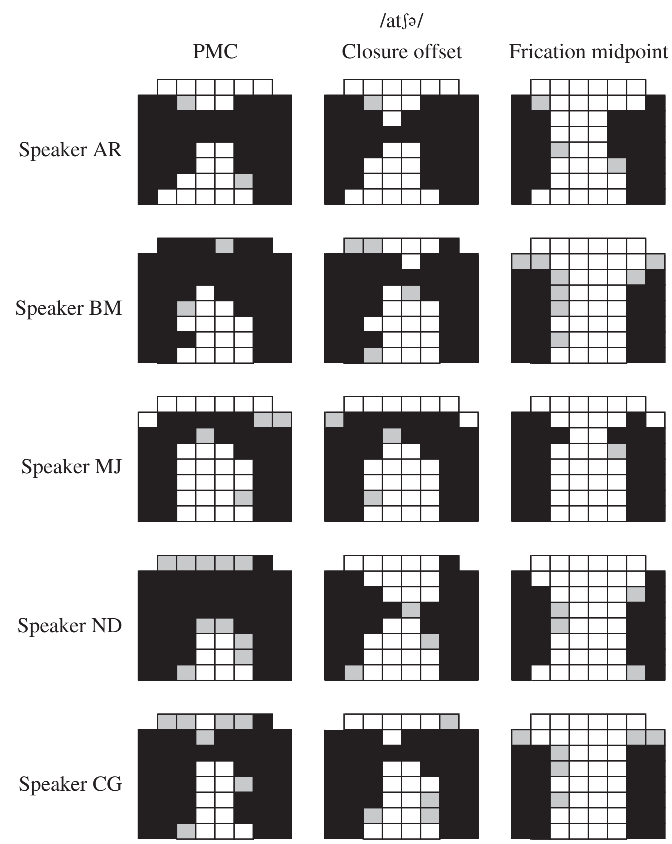

Fig. 5. Linguopalatal contact configurations for /tʃ/ in the sequence /atʃə/ at point of maximum contact or PMC, closure offset and frication midpoint for all Majorcan Catalan speakers. Electrodes have been assigned different colour shades depending on frequency of activation across tokens, i.e., black (80–100%), grey (40–80%) and white (0–40%).

A comparison between /k/ and /tʃ/ should be carried out mostly at closure offset and during the frication noise since the perceptual identification of the two sounds ought to be based on their frication acoustic properties. At closure offset, a comparison between Figs. 1 and 5 reveals that the two consonants share a similar postalveolar closure location for speakers AR and CG but not for the other speakers for whom the stop is more posterior than the affricate. Inspection of the EPG patterns at closure offset and at frication midpoint for [c] shows that four speakers also exhibit a narrow constriction passage about two free electrodes wide, either behind closure location over the palatal zone (for speaker CG and, less so, for speaker AR) or else in front of closure location (for speaker BM and, less so, for speaker MJ). This means that, at the time the stop closure is completely released, a narrow channel extending over the back alveolar region and the entire palatal zone (yielding a more [ʃ]-like noise) or just along the palatal zone (yielding a more [ç]-like noise) is obtained. Since this constriction slit also occurs for the affricate, it may be hypothesized that the noise spectral properties of the two sounds are potentially confusable for all four speakers taken into consideration. Whenever the constriction extends exclusively over the whole palatal zone or a back portion of it (as for speakers MJ and ND), the outcoming affricate [tç] could very well be integrated as /tʃ/ if this is the only affricate available in the language's phonological system.

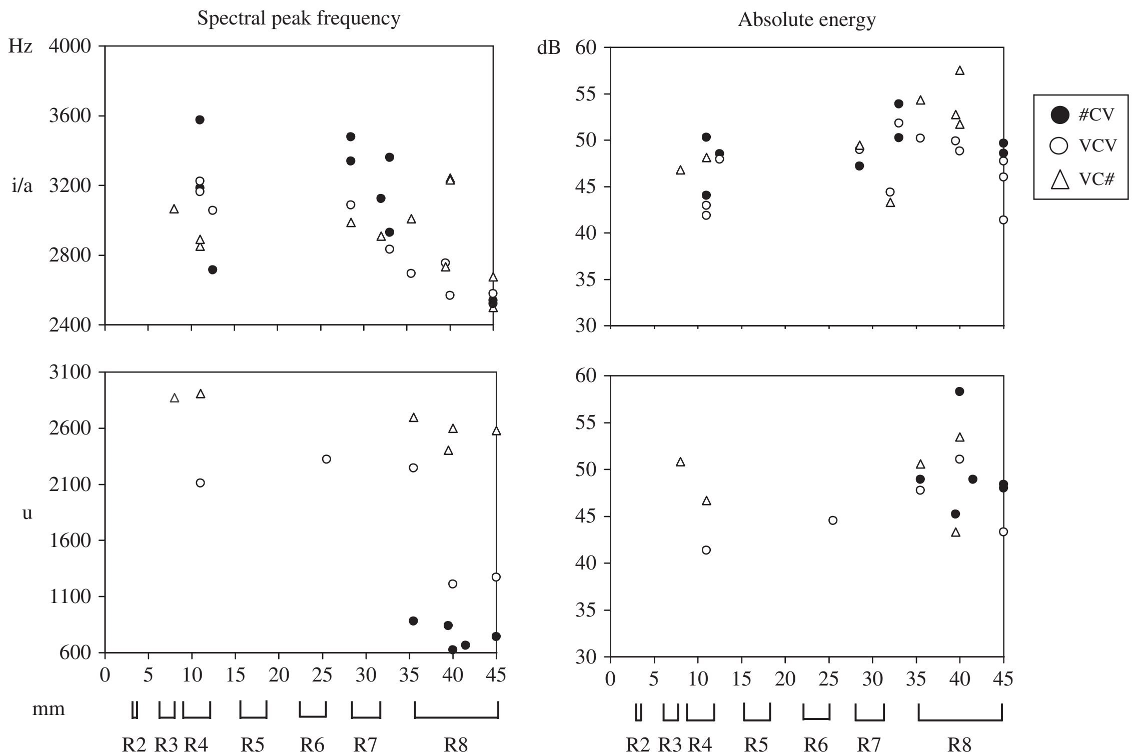

Fig. 6. Variations in burst spectral peak frequency (left) and in burst absolute energy (right) as a function of front-cavity length measured at closure offset. Data correspond to word/utterance initial, intervocalic and word/utterance final /k/ in the context of the vowels /i, a/ (top graphs) and /u/ (lower graphs) for all speakers. The subdivisions along the abscissa axis correspond to distance ranges in mm between row 1 and each of the rows 2–8 for all speakers.

2.2.1.3. Burst spectral peak. Fig. 6 (left) displays frequency variations for the burst spectral peak as a function of front-cavity length sampled at closure offset. Data have been plotted separately for contextual /i, a/ (top) and /u/ (bottom) since lip rounding is expected to increase the front-cavity length and to lower the burst spectral frequency. Articulations produced behind row 8 are represented together with those articulated at this row. Subdivisions along the horizontal axis correspond to the distance ranges between row 1 of electrodes and each of the more posterior rows 2–8 for all five speakers under analysis (see Table 2). Thus, the distance range labeled R2 is 3.5–4 mm because rows 1 and 2 are 3.5–4 mm apart when data for all subjects are taken into consideration.

Articulatory–acoustic variations for the /i, a/ condition indicate that, whether compared with changes in closure location at closure offset (Fig. 6, left) or at PMC (not shown), the burst spectral peak rises from about 2600 Hz to about 2800−3500 Hz as place of articulation moves forward from the postpalate (at row 8) to the prepalate (at rows 5 and 6), and remains at this frequency as place of articulation is fronted over more anterior rows of electrodes at the alveolar zone. These values are in the range of those for /tʃ/ for the same five Majorcan speakers, i.e., between 2800 and 3200 Hz, reported in Table 3. We take this finding as evidence that fronting the (alveolo)palatal stop closure may cause the stop burst to reach an analogous spectral frequency peak to that for the frication period of /tʃ/. The two bottom graphs in the figure show that the burst spectral peak in the context of /u/ may also increase as closure is fronted, i.e., from a very low frequency at about 600–900 Hz for /#ku/ and occasionally at 1000–1200 Hz for /uku/ up to a much higher peak at about 2000–3000 Hz for /uk#/ and /uku/ which may also be available when closure location occurs at row 8.

Statistical results indicate that contextual and position-dependent differences in burst spectral peak frequency are highly similar to those reported for the articulatory measures CA and Q. There was a main effect of ‘vowel’ ($F\,(1.1, 4.4) = 130.65$, $p = 0.000$) and ‘position’ ($F\,(2,8) = 12.08$, $p = 0.004$), and a ‘vowel’ × ‘position’ interaction ($F(4,16) = 46.08$, $p = 0.000$), which, as revealed by mean values in Fig. 7 (upper left graph), are associated with differences for /i, a/ > /u/ mostly word initially and intervocalically and for VC# > VCV > #CV in the /u/ context condition. All sequences share a similar burst spectral peak frequency at about 2700–3300 Hz except for /#ku/ and, less so, /uku/ which exhibit a lower peak frequency. Based on these data and on those for /tʃ/, it may be hypothesized that the stop is prone to be heard as /tʃ/ in practically all contextual and positional conditions under analysis except word/utterance initially before /u/.

2.2.1.4. Burst energy. Fig. 6 (right) displays variations in absolute burst energy as a function of front-cavity length at closure offset for the vowel conditions /i, a/ (top graph)

Table 3
Mean acoustic values for /tʃ/ in the sequence /atʃə/ according to each Majorcan speaker and across speakers.

	Frication spectral peak (Hz)	Frication absolute energy (dB)	Frication relative energy	Frication duration (ms)	F2 transition endpoint (Hz)	F3 transition endpoint (Hz)	F2 transition range (Hz)	F3 transition range (Hz)
Speaker AR	3223	53.3	0.73	65.7	1625.1	2545.7	151.7	68.6
		1.8	*0.02*	*5.3*	*68.5*	*156.2*	*130.2*	*207.9*
Speaker BM	3027	65.4	0.94	58.6	1684.4	2716.9	85.9	109.1
		3.01	*0.04*	*6.9*	*108.8*	*47.4*	*80.4*	*73.6*
Speaker MJ	3125	56.1	0.81	82.9	1591.9	2198.6	140.6	9.3
		1.99	*0.03*	*23.6*	*69.2*	*66.4*	*69.6*	*146.4*
Speaker ND	2969	59.5	0.87	54.3	1650.4	2172.3	209.0	−98.0
		3.89	*0.03*	*11.3*	*85.2*	*187.5*	*87.8*	*121.9*
Speaker CG	2813	52.8	0.76	88.6	1674.0	2236.7	129.7	−20.1
		1.69	*0.03*	*9.0*	*82.0*	*94.6*	*49.7*	*94.6*
Mean	3031.4	57.42	0.82	70.02	1645.2	2374.0	143.4	13.8
sd	*155.79*	*5.32*	*0.08*	*16.1*	*86.0*	*249.3*	*91.7*	*147.9*

Standard deviations are given in italics.

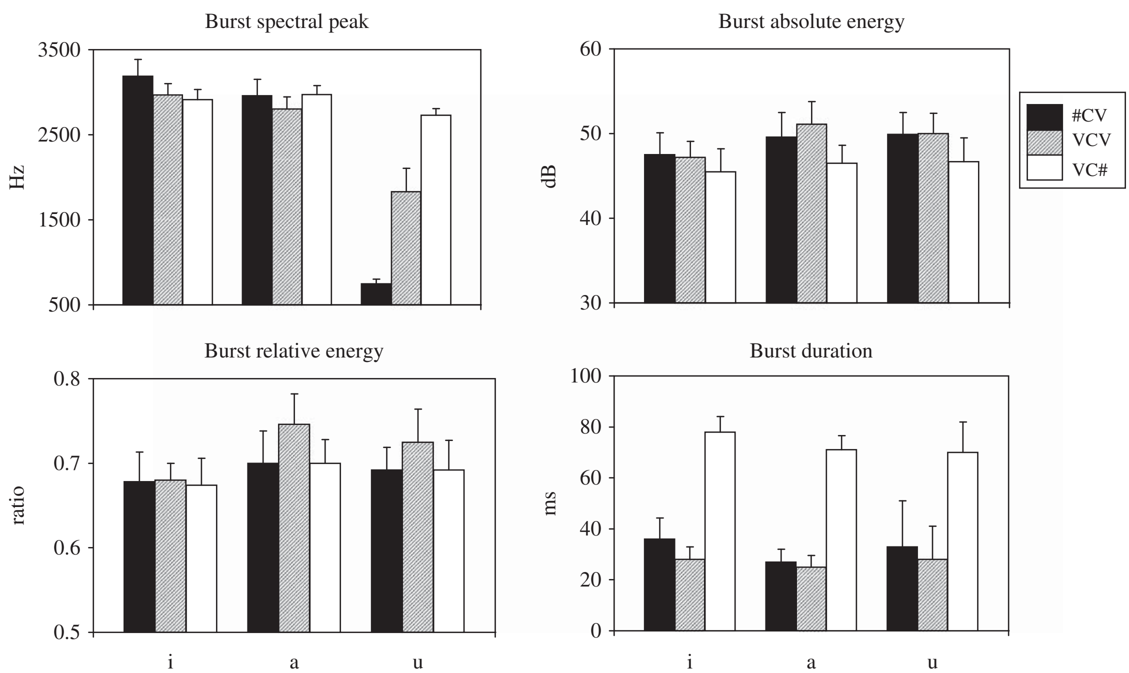

Fig. 7. Cross-speaker mean burst spectral peak, absolute and relative energy and duration values and standard deviations for word/utterance initial, intervocalic and word/utterance final /k/ in the context of /i, a, u/.

and /u/ (bottom graph). In comparison to /tʃ/ (see Table 3), the stop burst exhibits lower absolute energy values (40–55 dB for the stop, 50–65 dB for the affricate) and relative energy ratios (0.6–0.8 for the stop, 0.75–0.95 for the affricate). Moreover, this difference becomes greater for especially anterior (alveolo)palatal stop closures. This is so since both absolute and relative energy values for the stop burst decrease by about 10 dB and 10% as the stop closure is fronted from the postpalate to the alveolar zone and the front-cavity length shortens from about 35–45 mm to about 10 mm (see Fig. 6 regarding the absolute burst energy measure). Consequently, a considerable energy increase appears to be needed for (alveolo)palatal stops to be perceived as affricates.

Statistical results reveal important contextual and positional differences in burst energy with respect to CA, Q and burst spectral peak frequency. As revealed by the mean values presented in Fig. 7 (upper right and lower left graphs), burst energy was affected significantly by ‘vowel’ in the progression /a/ > /i/ (absolute energy, F (1.7, 6.9) = 6.01, $p = 0.033$; relative energy, F(1.3, 5.2) = 7.79, $p = 0.03$), and by ‘position’ in the progression intervocalic > final (absolute energy, F (1.3, 5.2) = 7.21, $p = 0.038$). Therefore, the burst appears to be especially intense in the context of low and, less so, back rounded vowels, and in intervocalic position, though always less intense than the affricate frication noise.

2.2.1.5. Burst duration. Fig. 7 (bottom right graph) shows that the burst frication period is much longer for final /k/ (about 70–80 ms) than for non-final /k/ (less than 40 ms). Accordingly, RM ANOVAs indicate that differences in burst duration are exclusively associated with 'position' (F (1, 4.1) = 14.92, $p = 0.017$). A comparison with frication duration values for the affricate presented in Table 3 (about 55–90 ms) reveals that only bursts for word/utterance final stops exhibit a comparable duration to the /tʃ/ frication period.

Inspection of the spectrographic displays indicates that word/utterance final /k/ does not lack a closure phase or a burst spike. Its closure period (115–140 ms) is slightly shorter than that for word/utterance initial /k/ (120–175 ms) and much longer than that for intervocalic /k/ (50–90 ms). Such an increase in closure and burst duration for word/utterance final /k/ is likely to be associated with prepausal lengthening.

2.2.1.6. Vowel transition endpoints. As shown in Fig. 8 (upper left graph), the F2 transition endpoints for Majorcan /k/ occur between 2200 and 2500 Hz in the context of /i/, between 1700 and 2000 Hz next to /a/, and below 1500 Hz in the context of /u/, those for /#ku/ being especially low (about 700 Hz). The F3 transition endpoints (upper right graph) occur at about 2900–3100 Hz in the context of /i/, 2300–2800 Hz in the context of /a/ and 2200−2500 Hz for contextual /u/. In most instances, these F2 and F3 endpoint values approach those for /tʃ/ in Eastern Catalan (Section 1.4) and in Majorcan in the context of /a/ (Table 3).

Contextual and positional effects for the F2 vowel transition endpoints match to a large extent those reported for articulation and for burst spectral frequency. Statistical tests yielded a significant effect of 'vowel' for /i/ > /a/ > /u/ (F (3,12) = 12.92, $p = 0.000$), a significant effect of 'position' for (V)CV > #CV (F (1.5, 6) = 93.76, $p = 0.000$), and a 'vowel' × 'position' interaction according to which the position-dependent differences just mentioned hold especially in the context of /u/ (F (2.5, 10.1) = 9.76, $p = 0.003$). Judging from the mean values in Fig. 8 and Table 3 and these statistical results, there appears to be a close match between the F2 transition endpoints for the stop and for the affricate in the case of /i/ in all positions, of /a/ mostly syllable initially, and perhaps of syllable initial /u/ in VCV sequences (though F2 is lower than expected in this case).

The vowel transition endpoint values for F3 look quite similar to those for F2 in being highest in the context of /i/, but differ from them in that /#ku/ does not exhibit the lowest value of all sequences.

2.2.1.7. Vowel transition ranges. Data plotted in Fig. 8 (bottom left graph) and those given in Table 3 reveal that the F2 vowel transition ranges for the (alveolo)palatal stop are generally positive and as high as and even higher than those for the affricate /tʃ/. RM ANOVAs yielded a significant effect of 'vowel' paralleling that for burst energy and thus, decreasing in the progression /a/ > /i/ (F (1.6, 6.6) = 8.27, $p = 0.018$). Therefore, the frequency extent of the F2 transition is clearly larger in the former vs. latter

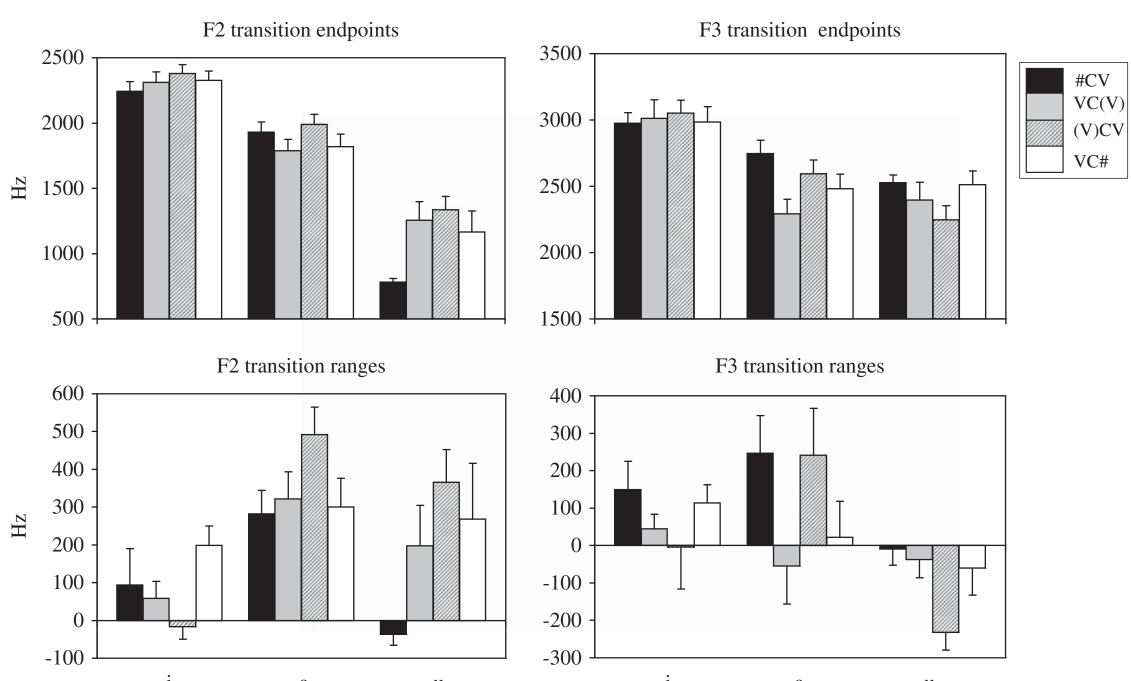

Fig. 8. Cross-speaker mean F2 and F3 transition frequency endpoints (top) and ranges (bottom) and standard deviations for word/utterance initial, intervocalic and word/utterance final /k/ in the context of /i, a, u/. Data for the intervocalic condition have been split into those for VC(V) and (V)CV.

vowel context, that for /u/ falling in between. Also in parallel to statistical results for the burst energy data, there was a significant effect of 'position' (F (1.7, 6.9) = 6.82, $p = 0.025$) and a significant 'vowel' × 'position' interaction (F (5.5, 21.9) = 6.39, $p = 0.001$) according to which transition ranges happen to be larger in intervocalic syllable initial position ((V)CV) than word initially (#CV) in the context of /a, u/, and word finally (VC#) than intervocalically ((V)CV) in the context of /i/.

F3 transition ranges for the stop and the affricate (see Fig. 8, bottom right graph, and Table 3) are highly speaker dependent and, therefore, hard to compare with each other. Those for the stop resemble the F2 transition ranges in being positive and salient for the (V)CV condition in the context of /a/, and differ from them in being negative also for the (V)CV condition in the context of /u/.

2.2.1.8. Summary. The (alveolo)palatal stop resembles the alveolopalatal affricate regarding frication spectral frequency which is equally high for both consonants, but not regarding frication intensity and duration which are greater for the affricate than for the stop. Moreover, closure location for [c] matches that for /tʃ/ for some speakers, and the two consonants exhibit an analogous long narrow constriction during the frication phase for most speakers.

Contextual and positional effects argue in favor of the attested fact that velar softening may operate in non-front vowel contexts, thus supporting the articulation-based hypothesis but not the acoustic equivalence hypothesis according to which velar softening ought to occur before front vocalic segments only. Burst spectral peak and F2 vowel transition endpoint frequency values suggest that the (alveolo)palatal stop realization of /k/ is prone to be heard as /tʃ/ in practically all contextual and positional conditions except for /#ku/ where /k/ stays velar. Moreover, burst energy values and F2 transition ranges suggest that velar softening should apply especially before /a/ and, less so, before /u/ preferably in intervocalic syllable initial position. Word/utterance final (alveolo)palatal stops are expected to be integrated as affricates or fricatives judging from their especially long burst. A trend towards articulatory reinforcement of the (alveolo)palatal realization of /k/ in word/utterance initial position does not appear to be matched by the burst and vowel transition frequency characteristics.

2.2.2. Principal component analysis

Results obtained from the principal component analysis indicate that the individual test variables may be reduced to three independent factors:

(a) Factor 1 accounts for 41.13% of the variance and, as shown in Table 4, encompasses the measures CA, Q, burst spectral peak and F2 transition endpoint which exhibit high positive loadings above 0.80. All four measures were highly correlated, i.e., CA and Q ($r = 0.97$), CA and Q, and burst spectral peak and F2 transition endpoint (0.85, 0.80, 0.67 and 0.56), and burst spectral peak and F2 transition endpoint (0.81). Moderate positive loadings at about 0.60 were obtained for the F3 transition endpoint and range measures. Highly correlated measures in factor 1 appear to be associated with a frequency rise of the burst spectral peak as closure becomes more anterior, and of the F2 vowel transition endpoint as dorsopalatal contact size increases. They are also inversely related to lip rounding.

(b) Factor 2 accounts for 25.6% of the variance, and encompasses two measures exhibiting high positive loadings above 0.80, namely, burst energy and F2 vowel transition range. As expected, there was a high correlation between absolute and relative burst energy (0.75), as well as between (relative) burst energy and F2 vowel transition range (0.82). Correlated variables in Factor 2 are related to a rise in acoustic prominence of the stop burst as the articulatory distance between the stop and the vowel increases.

(c) Factor 3 accounts for 19.9% of the variance and, as indicated in Table 4, is associated with high and inversely related loadings for burst duration and burst absolute energy. The two measures were inversely correlated ($r = -0.79$). In comparison to the other two factors, factor 3 appears to be associated mostly with burst duration.

Table 4
Loadings for the first, second and third factors according to results from a principal component analysis performed on variables associated with the linguopalatal contact, burst and vowel transition characteristics of /k/ in Majorcan.

	Factor 1	Factor 2	Factor 3
CA	0.872	0.080	−0.298
Q	0.845	−0.015	−0.307
Burst spectral peak	0.961	0.005	−0.140
Burst absolute energy	−0.346	0.501	0.770
Burst relative energy	−0.158	0.882	0.386
Burst duration	0.116	−0.061	−0.854
F2 transition endpoint	0.869	−0.246	0.026
F3 transition endpoint	0.603	−0.761	0.525
F2 transition range	0.264	0.935	0.137
F3 transition range	0.608	−0.098	0.151

Factor scores have been displayed in two scatterplots representing those factor combinations which were judged to be most informative, i.e., factor 1 × factor 2 and factor 2 × factor 3 (see Fig. 9). Based on the factor loadings reported in Table 4, values for factor 1 are expected to vary directly with the frequency of the burst spectral peak and the F2 transition endpoint, values for factor 2 to vary directly with burst energy level and F2 transition range, and values for factor 3 to vary inversely with burst duration. Each point in each plot corresponds to one of the nine #CV, VCV and VC# sequences under analysis.

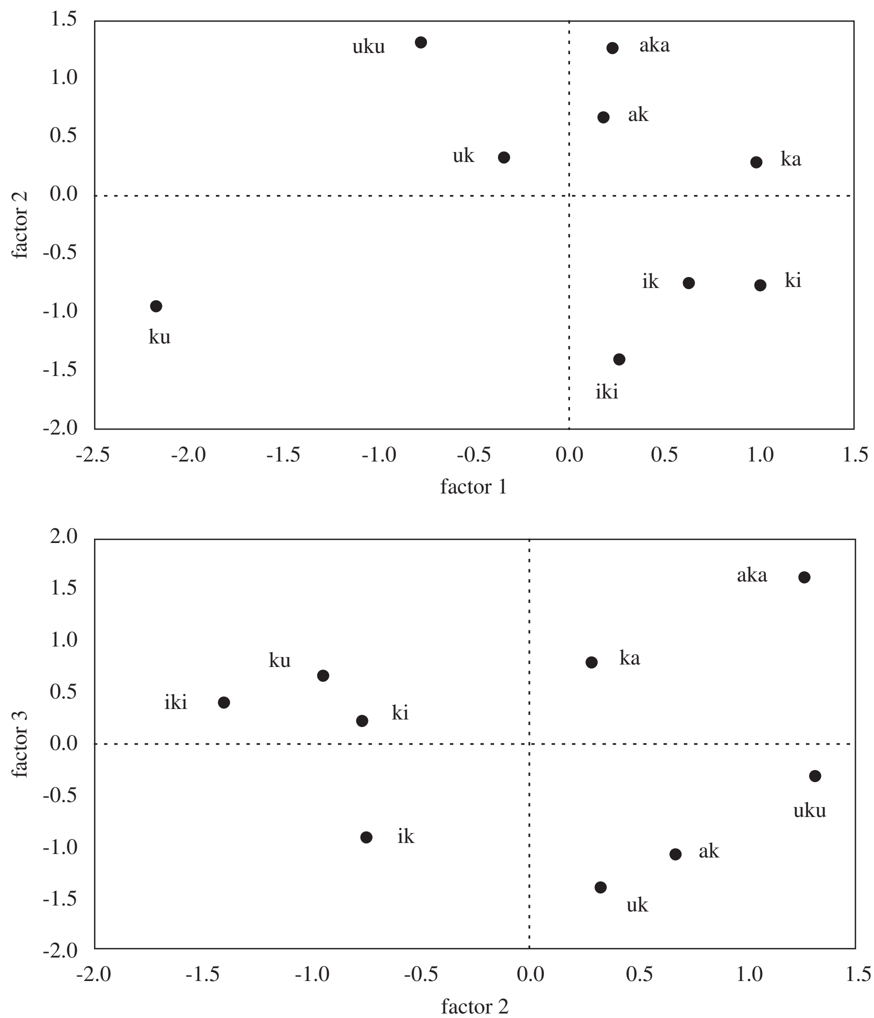

Fig. 9. Factor 1 × factor 2 and factor 2 × factor 3 scatterplots representing the #CV, VCV and VC# sequence groupings according to results obtained from the principal component analysis.

The factor 1 × factor 2 scatterplot indicates the existence of three main groups of sequences, i.e., a group encompassing all sequences with /i/, another group composed of all sequences with /a/ and /u/ except for /#ku/, and a third group with the word/utterance initial sequence /#ku/ only. Assuming that /tʃ/ should exhibit high values for both factors, this triple subdivision reinforces the notion that velar softening should not occur for /#ku/ and is more prone to take place in the context of /a, u/ than in the context of /i/ based on the contribution of factor 2. Other less obvious differences may be found in the same plot. Regarding factor 1, sequences with /a/ show a higher value than those with /u/ matching mostly frequency differences at the F2 transition endpoint between the two vowel contexts, and word/utterance initial /#ki, #ka/ exhibit higher values than /iki, ik#, aka, ak#/ presumably in line with differences in linguopalatal contact fronting rather than with acoustic differences (Section 2.2.1.1). On the other hand, factor 2 exhibits higher values for /aka, uku/ than for /#ka, ak#, uk#/ and lower values for /iki/ than for /#ki, ik#/, which is in accordance with the presence of maximal burst energy values and F2 formant transition ranges in intervocalic sequences with low and back vowels (Sections 2.2.1.4 and 2.2.1.7).

Factor 3 in the factor 2 × factor 3 scatterplot separates /ik#, ak#, uk#/ from the remaining sequences. This double subdivision is in agreement with the existence of an especially long burst word/utterance finally.

These PCA results are highly consistent with the phonetic description of the individual variables summarized in Section 2.2.1.8. The frequency characteristics of both the burst and the vowel transitions for /k/ are expected to reinforce each other in cueing perceptually velar softening in all contexts and positions except for /#ku/. Moreover, burst intensity and the F2 formant ranges should render velar softening most feasible for /VkV/ sequences with low and back vowels. Burst duration could favor velar softening word/utterance finally.

3. Experiment 2 (perception)

The goal of this section is to test whether the realization [c] of /k/ is most prone to be heard as /tʃ/ in those contextual and positional conditions where the two consonants exhibit similar acoustic properties. This possibility will be explored through a series of perception tests using a selected set of stimuli taken from the data sample subjected to analysis in Section 2.

3.1. Method

3.1.1. Changes in burst energy level

The analysis results reported in Section 2 suggest that the stop burst was not prominent enough for syllable initial /k/ before /i/ to approach /tʃ/, and that this was related to burst energy rather than to burst spectral frequency or duration. According to our auditory impression, only a small subset of Majorcan sequences submitted to acoustic analysis yielded a /tʃ/ percept, i.e., /aka/ for speaker AR and /uku/ for speakers AR, BM and CG. A special case was the burst for word/utterance final /k/ which could be heard as the palatal fricative [ç] rather than as an affricate. These auditory judgments are consistent with the observation that unaspirated stops are generally too weak to be categorized as affricates. For these reasons, we decided to increase the energy level of the stop burst so that it could approach that of an affricate under the assumption that such an increase is prone to occur at the edges of prosodic constituents and in lexically stressed and accented syllables.

The motivation for a burst energy rise in strengthening conditions deserves justification. Studies from the literature have shown that tongue contact, intraoral pressure, and closure and burst duration for stops may increase with prosodic prominence. An increase in linguopalatal contact has been reported to occur in stressed position (for Italian /t, d/; Farnetani, 1990), and utterance initially and finally (for English /t, d, n/; Fougeron & Keating, 1997; Keating et al., 1999). Other studies report an increase in peak intraoral pressure utterance initially and before a stressed vowel (Brown & Ruder, 1972; Malécot, 1970), and in closure duration in stressed, accented and domain initial positions (for Korean /t, t^h, n/ and lenis /t/, and for Dutch unaspirated /t, d/; Cho & Keating, 2001; Cho & McQueen, 2005). Variations in burst duration as a function of stress, focus, speaking rate and position within the prosodic constituent appear to take place in languages where stops are aspirated but not in languages where stops are unaspirated perhaps since the stop voicing cue is delayed VOT in the former language group and closure voicing in the latter (Solé, 2007).

Data reported in the literature are unclear as to whether an increase in prominence causes an increase in burst energy in the consonant, the adjacent vowel or both. Some studies referred to above conclude that prominence does not yield a substantial increase in consonant energy (Cho & Keating, 2001; Cho & McQueen, 2005). Other studies have found, however, that, as prosodic boundary strength increases, the acoustic energy of the initial consonant may increase with respect to that for the following vowel (for French /n, l/; Fougeron, 1998, 2001). Finally, other literature sources report an increase in stop burst and vowel intensity in stressed and/or accented position (for Dutch /t, d/ and for Hindi /p, b, p^h, b^h/; Cho & McQueen, 2005; Dixit & Shipp, 1985) or at the beginning of an intonational phrase (for English /n/; Cho, McQueen, & Cox, 2007). This latter finding suggests that initial stressed CV syllables could behave as cohesive units such that prominence causes the consonant to become more constricted and the vowel to become more open (Farnetani & Kori, 1986).

Fougeron's findings for French reported above suggest that syllable reinforcement may result in an increase in relative energy between the consonant and the vowel. Based on this outcome we manipulated the velar stop bursts of our perception stimuli by raising their relative energy so as to render them affricate-like. Other acoustic properties were left unchanged, namely, burst duration which, as stated above, does not seem to be affected by an increase in prominence for unaspirated stops, and closure duration which could not be lengthened postpausally (initial /k/ in our perception stimuli occurred after pause only; see Section 3.1.2) and was sufficiently long prepausally.

As pointed out in the Introduction, an increase in burst energy for (alveolo)palatal stops may be associated with the formation of a narrow lingual constriction at closure release. Linguopalatal contact patterns in Fig. 1 confirm the existence of an (alveolo)palatal constriction narrowing at closure offset and during the burst frication phase for [c] which may account for why listeners may sometimes hear a [j]-like sound towards the end of the consonant. According to the articulatory-based explanation, the claim is that an increase in airflow passing through this (alveolo) palatal constriction in prominent prosodic conditions could generate a high energy burst frication noise which could resemble the frication noise of a front affricate. If this claim is correct the aerodynamic factors involved in the implementation of velar softening would not differ much from those involved in the transformation of /t, d/ before a front vocalic segment into [tʃ, dʒ] (Ohala, 1983, 1985). Data on German and Polish (Hall, Hamann, & Zygis, 2006) show that assibilation is related to burst frication duration and more prone to affect /tj/ than /ti/ and /dj/ than /di/. During the production of the alveolar stop in these sequences, a narrower constriction for /j/ than for /i/ may offer a greater impediment to the air escaping from the mouth, thus causing a delay in the transglottal pressure differential which results in a longer /t/ and /d/ friction phase.

3.1.2. Stimuli preparation

The tokens exhibiting the longest release for each #CV, VCV and VC# combination and for each speaker were selected as stimuli for the perception tests. Some productions were excluded: those for the speaker ND since they did not vary in closure location and had very short bursts; speaker CG's (palato)velar realizations of /k/ in the strings /aka, ak#, uk#/ for reasons pointed out in Section 2.2.1.1. Overall, there were 36 stimuli (9 sequences × 4 speakers). The perception stimuli contained the closure period, the stop burst, and the first 100 ms of the following vowel in the case of the #CV and VCV condition or the last 100 ms of the preceding vowel in the case of the VC# condition (see also Guion, 1998).

The procedure for rendering the relative energy level of the stop burst analogous to that for /tʃ/ is described next. First, the relative energy values for the affricate were averaged across tokens for each speaker. Then, for each selected token of the sequences /#ki, #ka, #ku, iki, aka, uku, ik#, ak#, uk#/, the relative energy of the stop burst was rendered the same as that for /tʃ/ by multiplying the burst absolute energy by an appropriate factor. This transformation procedure was applied to all temporal frames of the burst portion following the initial spike. No attempt was made to model the affricate rise time, i.e., an amplitude increase occurring during the first half of the frication period of the affricate, since it is not clear whether this parameter contributes to the distinction between affricates and consonants of other manners of articulation (Howell & Rosen, 1983). Overall, the average increase in absolute burst energy across speakers was 11.5 dB (from a mean of 49.1 dB for the stop to a mean of 60.6 dB for the affricate) and the average increase in relative energy was 0.18 (from 69% for /k/ to 87% for /tʃ/). Similar changes in the amplitude of the stop burst have been carried out in previous perception experiments (Repp, 1984). It should be kept in mind that the stimuli resulting from the manipulation of the burst energy level were still stop-like regarding the closure and frication duration cues, which have been shown to play a relevant role in the perceptual distinction between stops and affricates (Repp, Liberman, Eccardt, & Pesetsky, 1978).

In order to eliminate the speaker-dependent differences in overall acoustic energy among perception stimuli, the highest energy value of all stimuli was divided by the energy value of each stimulus and the latter was multiplied by the resulting ratio. In all cases, the energy values used for the normalization procedure were taken 50 ms inside the vowel following /k/ (for the #CV and VCV sequences) or preceding /k/ (for the VC# sequences) on 10 ms window energy contours including the entire sequence. The application of this energy normalization criterion did not affect the inherent amplitude difference between the consonant and the vowel.

3.1.3. Test administration

Three tests were prepared and given to Catalan informants.

Test I had excerpts with /k/ whose burst energy level had been increased using the procedure explained above. This test included 180 stimuli, i.e., 5 repetitions of the 36 sequences and 20 warm-up stimuli. Stimuli were organized in 18 blocks of 10 stimuli; successive stimuli within each block were separated by 3 s intervals, and successive 10 stimuli blocks by 10 s intervals. They were played on loudspeakers to two groups of unpaid university students, namely, to a group of 18 Majorcan Catalan speakers and to another group of 15 speakers of Eastern Catalan. The speakers of the former group are acquainted with palatal stops either because they use them themselves or because they hear them from other speakers on a daily basis, while the speakers of the latter group do not have the palatal stop allophone of /k/ in their sound inventory but may hear it from Majorcan speakers.

The perception test lasted for about 20 min. Subjects were asked to identify each stimulus as either /k/ or /tʃ/ on an answer sheet by writing 'K' for the stop and 'TX' for the affricate. The digraph tx is commonly used in the orthographic representation of /tʃ/ in Catalan. The voiceless affricate occurs in the phonemic inventory of the Majorcan and Eastern dialects spoken by the two groups of informants.

Tests II and III differed from Test I in that, in addition to stimuli with /k/, they also included excerpts with natural speech productions of /tʃ/ so as to avoid a possible bias in favor of the affricate responses. The two tests differed from each other in that the burst energy level was increased in the former test and was kept unmodified in the latter. In order to render all perception tests equally long, speaker MJ's stimuli were excluded from both tests since they had yielded a considerably low number of /tʃ/ identification responses in Test I.

Tests II and III also had 180 stimuli. The number of stimuli with /k/ was 108 (4 tokens × 9 sequences × 3 speakers). The number of stimuli with /tʃ/ was 72 and included 4 tokens of /tʃV/ and 4 tokens of /Vtʃ/ with the vowels /i, a, u/ uttered by speakers AR, BM and CG (4 tokens × 6 sequences × 3 speakers). All /tʃ/ excerpts were extracted from productions of meaningful words embedded in short Catalan sentences, i.e., ratxa ['ratʃə] in the sentence és una ratxa bona 'It is a lucky stroke' and raig [ratʃ] in the sentence cada dia un raig 'a sip every day'. All stimuli were normalized using the same criteria described in Section 3.1.2.

Tests II and III were played under the same conditions as Test I to a single group of 12 unpaid Eastern Catalan speaking university students. None of the informants who took Tests II and III had taken Test I.

3.2. Results

3.2.1. General findings

Fig. 10 presents mean /tʃ/ identification percentages for all perception tests. The first thing to notice about the figure is that the three test conditions yielded highly similar /tʃ/ identification percentages for each original sequence. This means that increasing the burst energy level or adding

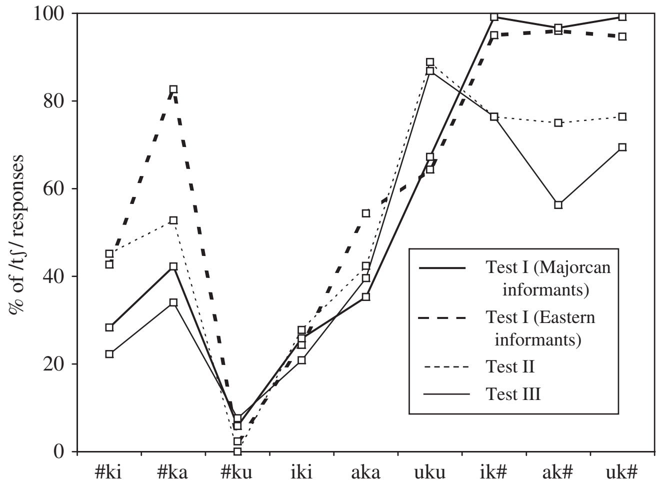

Fig. 10. Percentages of /tʃ/ identification for Tests I–III. Perception results for Test I are given separately for the Majorcan and for the Eastern informants.

affricate stimuli did not substantially affect the listeners' responses and, therefore, that the acoustic cues for velar softening in the (alveolo)palatal stop consonant are highly robust.

Generally speaking, identification percentages for word/utterance initial /k/ were close to 0% in the case of /#ku/ and lower for /#ki/ than for /#ka/, those for intervocalic /k/ varied in the progression /uku/ > /aka/ > /iki/, and those for word/utterance final /k/ were fairly high in all three vowel conditions. These perception results are consistent with the analysis data presented in Section 2 in pointing to /a/ and, to a lesser extent, /u/ as better velar softening triggers than /i/, and in predicting that velar softening cannot affect the sequence /#ku/. Regarding the former finding, they indicate that burst energy and vowel transition ranges are prominent velar softening cues which may operate not only word initially but intervocalically as well. Identification percentages for all three VC# sequences were unexpectedly high perhaps since our informants identified as /tʃ/ those stimuli which sounded [ç]-like and thus, were halfway between [c] and [tʃ] (see Section 3.1.1). As suggested earlier, listeners may have paid special attention to the long duration of the stop burst frication period in these circumstances.

Percentages of /tʃ/ identification were higher for some speakers than for others. In all tests this was mostly so in the case of /aka/ for speaker AR (about 80% /tʃ/ responses) than for the other three speakers (about 10–20%). Inspection of the acoustic characteristics of this sequence reveals that neither the burst spectral frequency, energy or duration or the vowel transition endpoints and ranges account for this difference. Instead, the most salient phonetic property appears to be the presence of an (alveolo)palatal channel at stop release starting at rows 4–5, moving backwards continuously for about 80 ms and ending at the more posterior rows 7–8, thus giving rise to a slow lowering F2 transition. As for the other speakers, this channel lasts for about 50 ms thus generating a faster lowering F2 transition (for speaker CG), or else occurs at a much more retracted location at the back palate (for speakers BM and MJ).

The number of /tʃ/ reponses was also affected by dialect and by the presence or absence of /tʃ/ excerpts in the perception test. As shown in Fig. 10, among subjects who took Test I, Majorcan informants reported less /tʃ/ responses than Eastern informants in the case of the sequences /#ki, #ka, aka/. This dialect-dependent difference suggests that speakers who were more familiar with the (alveolo)palatal stop must have expected the perceptual stimuli to be more [c]-like in order to categorize them as /tʃ/. Moreover, a comparison between the number of /tʃ/ responses elicited by the two groups of Eastern Catalan speakers who took Test I and Test II shows, as predicted, higher identification percentages for /#ka, aka, ik#, ak#, uk#/ in the former test without /tʃ/ excerpts than in the latter test with /tʃ/ excerpts.

3.2.2. Increase in burst energy level

The number of /tʃ/ responses may also increase with an increase in burst energy level. Fig. 11 shows for each sequence the increment in burst absolute and relative energy value between the unmodified condition in Test III and the modified condition in Test II, and the corresponding increase in /tʃ/ identification percentages. It may be seen that an increase in energy level causes a substantial increase in /tʃ/ responses for /#ki, #ka, ak#/ but not for /#ku, iki, aka, uku, ik#, uk#/. As pointed out below, there may also be differences in the amount of /tʃ/ identification responses depending on the speaker.

The most interesting scenario is that for /#ki/ since the increase in /tʃ/ responses in this case turned out to be

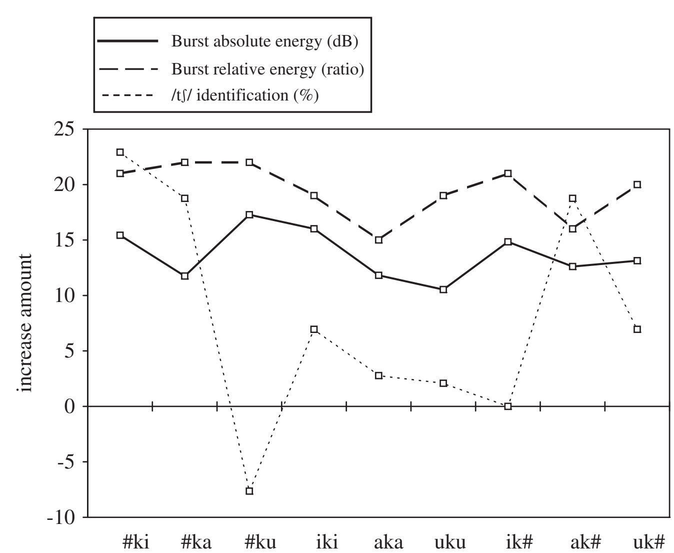

Fig. 11. Size of the increase in /tʃ/ identification percentages between Test II and Test III (dotted line) matched against the corresponding increase in burst absolute and relative energy values (continuous and discontinuous lines, respectively). Energy values are expressed in dB (absolute) and in burst/vowel energy ratios multiplied by 100 (relative).

associated mostly with speaker BM whose burst frication noise happened to be the most intense of all speakers both in the original and modified /#ki/ stimuli. Thus, the increase in /tʃ/ judgments was 75% for the speaker BM's stimuli and about 0% for the AR's and CG's excerpts, while the stop burst absolute energy values were 56.3 dB for BM, 42.2 dB for AR and 39.4 dB for CG in the original stimuli and 70.2 dB for BM, 56.8 dB for AR and 57.1 dB for CG in the modified stimuli. The finding that the /#ki/ stimuli exhibiting the highest burst energy level were the ones yielding the highest percentage of /tʃ/ responses supports the notion that the burst frication noise needs to be really prominent for the (alveolo)palatal stop before /i/ to be heard as an affricate.

An increase in burst prominence level for the sequence /#ka/ improved the identification of /k/ as /tʃ/ to a similar degree for all speakers' stimuli, thus confirming results from the production analysis indicating that the (alveolo) palatal stop burst and the vowel transitions are good velar softening cues in this case. On the other hand and analogously to the /#ki/ scenario, an increase in the number of /tʃ/ responses in the case of the sequence /ak#/ was found to hold mainly for speaker BM who turned out to exhibit the most intense burst frication period of all speakers. The increase in /tʃ/ judgments for /ak#/ was 29.2% for BM, 22.9% for AR and 4.2% for CG, and the burst energy level was changed from 49.2 to 65.2 dB for BM, from 41.4 to 52.9 dB for AR and from 48.1 to 57.3 dB for CG.

For several sequences, an increase in burst energy did not cause a significant improvement in the percentage of /tʃ/ responses for specific reasons. In the case of /#ku/, the low-frequency component of the burst and the vowel transitions ensures that the velar stop will always be categorized as such independently of burst energy level and other acoustic factors. As for /aka, uku/, this may have been so because the stop burst was already loud in the unmodified version of the stimuli (see Section 2.2.1.4). Regarding possible differences in /tʃ/ identification among stimuli for different speakers, the /aka/ excerpts for speaker AR did much better than those for BM and CG presumably for reasons pointed out above (see Section 3.2.1), while the /uku/ stimuli for all speakers yielded about 80% /tʃ/ identification percentages consistent with the fact that all speakers' bursts were more or less equally intense in this case.

There was an instance where burst energy seemed to play no role in the results for the perception test. The (alveolo)palatal stop underwent a much smaller increase in /tʃ/ responses for /iki/ than for /#ki/ in the case of speaker BM's stimuli in spite of the fact that the burst energy increase was greater for /iki/ than for /#ki/ and that the two sequences exhibited a similar burst energy value in the modified condition (56.3 and 70.2 dB for /#ki/, 43 dB and 68.7 dB for /iki/). Inspection of spectrographic displays revealed that a noticeable difference between the two sequences resides in the burst spectral peak (3828 Hz for /#ki/ and 3125 Hz for /iki/), burst duration (50 ms for /#ki/ and 30 ms for /iki/) and perhaps the actual burst spike (which was longer and more intense word/utterance initially than intervocalically).

3.2.3. Summary

Results from the perception tests confirm the initial hypothesis that [c] may be identified as /tʃ/ even when the acoustic signal excised from natural speech productions remains unmodified. Moreover, in addition to the frequency component which excludes /#ku/ from the velar softening candidates, the percentage of /tʃ/ responses appears to be favored by a high burst energy level and large vowel transition ranges for the stop before the vowels /a/ and /u/. In agreement with the acoustic data reported in Section 2, there was no special trend for velar softening to be favored word/utterance initially than intervocalically. Word/utterance final /k/ may have yielded a high number of affricate responses due to the long /ç/-like or /ʃ/-like frication noise occurring at stop release. It was also found that those bursts which were already intense originally (including those for /#ki/) increased the number of /tʃ/ responses when amplified, which appears to be in support of the burst intensity raising procedure carried out for the preparation of some perception tests. For some sequences, the identification of [c] as /tʃ/ was more frequent for the productions of some speakers than for those of others presumably because the crucial tokens exhibited especially salient cues; this was so for /aka/ for speaker AR (presumably since this token exhibited prominent F2 vowel transitions) and for /#ki/ for speaker BM (presumably since the burst frication noise was especially intense in this case).

4. Summary and discussion

Articulatory, acoustic and perceptual data for Majorcan Catalan reported in this study indicate that velar softening may apply on (alveolo)palatal stop realizations of unaspirated /k/ involving much tongue contact after velar palatalization has taken place. With the exception of the sequence /#ku/, contact fronting causes an increase in the frequency of the burst spectral peak and of the vowel formant transition endpoints which may be a precondition for the burst frication noise to be categorized as the frication period of the alveolopalatal affricate /tʃ/. The analysis and perception results also reveal that a high burst energy level and large F2 transition ranges for [c] before /a/ in the sequences /#ka, aka/, and before /u/ in the sequence /uku/ (where /k/ was originally word final; see Section 2.1.1), are needed for velar softening to be perceived. (Alveolo) palatal stop productions may be prone to be heard as /tʃ/ in word–utterance final position where they exhibit an especially long burst frication noise. High /tʃ/ identification percentages for these phonetic realizations may have been partly due to the absence of the answer choice /ç/; data on sound change indicate that velar softening may also yield this phonetic outcome (see Section 1.2.2).

The replacement of /ki/ by /tʃi/ should depend on articulatory and acoustic characteristics which were not sufficiently present in the Majorcan stop productions subjected to analysis. The most obvious candidate is burst acoustic prominence. Data for one of the Majorcan speakers indeed suggest that a sufficient increase in burst energy level may cause [ci] to be heard as /tʃi/. Guion (1998) also found that an increase in VOT duration for /ki/ in English where the stop is aspirated contributes to an increase in the number of /tʃ/ responses. We have hypothesized that the articulatory event causing an increase in burst prominence is constriction narrowing at the closure release of an (alveolo)palatal stop.

These data argue in favor of the articulation-based hypothesis but not of the acoustic equivalence hypothesis of velar softening, mostly because this process has been shown to operate on (alveolo)palatal realizations of /k/ occurring in any vocalic context and position except before back rounded vowels word internally. Articulatory data for Majorcan speakers reveal that [c] exhibits similar articulatory and spectral properties to /tʃ/ (also to /tç/) which renders the identification of the stop and the affricate highly feasible. Our results are in agreement with evidence from sound change in Gallo-Romance and other language families showing that velar softening may take place through velar palatalization before low and central vowels and word finally. It has been proposed that velar palatalization in these circumstances may be implemented through strengthening of the (alveolo)palatal stop gesture in prominent prosodic conditions yielding a contact increase towards the front palate. Production and perception data for /uku/, where /k/ was realized as an (alveolo)palatal stop because it was taken from word final /k/, reveal that [c] may be integrated as /tʃ/ before high back rounded vowels as well. The reason why languages appear not to favor velar palatalization (and thus, velar softening) before back rounded vowels could be sought in the need to enlarge the front-cavity dimension for /k/ through lip rounding and closure backing in order to facilitate the production of the following vowel (see Section 1.3).

The acoustic equivalence hypothesis operates exclusively on postpalatal or postpalato-velar realizations of /k/ occurring before front vocalic segments. We believe that this hypothesis could still account for velar softening in the case of aspirated front velar stops, but not for unaspirated front velar stops or for velar stops occurring before non-front vocalic segments. Regarding aspirated front velar stops, the prominent frication period generated at the glottis and passing through a long and narrow postpalatal or palatovelar medial constriction could possibly yield a /tʃ/ percept. A more anterior and longer central channel along the (alveolo)palatal zone appears to be needed for a prominent burst to be associated with unaspirated front /k/. This articulation-based explanation is compatible with the presence of (alveolo)palatal stop allophones of front /k/ before /i, e, j/. As suggested in Section 1.3, it is also in agreement with the fact that velar palatalization occurred twice in different contextual conditions and positions in Romance, namely, earlier before front vocalic segments presumably through gestural blending and later on before other vowels and word finally through gestural strengthening.

Further research on velar softening should deal with modelling of the aerodynamic factors involved during (alveolo)palatal and velar stop production, with the articulatory and acoustic characteristics of (alveolo)palatal stops in different languages, and with the correlates of articulatory strengthening for unaspirated stops as a function of position, emphasis and stress. It should also explore the contribution of different acoustic cues to the /tʃ/ percept based on acoustic data alone and through their manipulation in perceptual experiments with synthetic speech.

Acknowledgments

This research was funded by projects HUM2006-03742 of the Ministry of Education and Science of Spain and FEDER, and 2005SGR864 of the Catalan Government. We would like to thank Marzena Zygis, Juliette Blevins, Joaquín Romero, Fernando Sánchez Miret, three anonymous reviewers and the participants at the ZAS Phonetics and Phonology 5 workshop for comments.

References

Anttila, R. (1972). *An introduction to historical and comparative linguistics*. New York: Macmillan.

Bhat, D. N. S. (1974). *A general study of palatalization*. Working Papers on Language Universals, Vol. 14 (pp. 17–58), Stanford University.

Bibiloni, G. (1983). *La llengua dels mallorquins. Anàlisi sociolingüística*. Ph.D. thesis, Universitat de Barcelona.

Blumstein, S. E. (1986). On acoustic invariance in speech. In J. Perkell, & D. Klatt (Eds.), *Invariance and variability in speech processes* (pp. 178–193). Hillsdale: Erlbaum.

Bouvier, J.-C. (1976). *Les parlers provençaux de la Drôme*. Paris: Klincksieck.

Browman, C. P., & Goldstein, L. (1989). Articulatory gestures as phonological units. *Phonology*, *6*, 201–251.

Browman, C. P., & Goldstein, L. (1992). Articulatory phonology: An overview. *Phonetica*, *49*, 155–180.

Brown, W. S., & Ruder, K. F. (1972). Phonetic factors affecting intraoral air pressure associated with stop consonants. In A. Rigault, & R. Charbonneau (Eds.), *Proceedings of the seventh international congress of phonetic sciences* (pp. 294–298). Mouton: The Hague.

Bruneau, Ch. (1913). *Étude phonétique des patois d'Ardenne*. Paris: Champion.

Brunner, V. R. (1963). Zur Physiologie der Rätoromanischen affrikaten tsch und tg (ch). In P. Zinsli (Ed.), *Sprachleben der Schweiz: Sprachwissenschaft, Namenforschung, Volkskunde* (pp. 167–173). Berne: Francke.

Buckley, E. (unpublished (a)). Velar fronting in Alsea. In Paper presented at the *Society for the study of indigenous languages of the Americas annual meeting*, 2007, Anaheim.

Buckley, E. (unpublished (b)). The phonetic origin and phonological extension of Gallo-Roman palatalization. In *North American phonology conference*, Vol. 1, 2000. Montreal: Concordia University.

Butcher, A. (2004). On the back of the tongue: Dorsal sounds in Australian languages. *Phonetica*, *61*, 22–52.

Carton, F. (1972). Un cas d'extension de la palatalisation dans les patois du nord de la France. In G. Straka (Ed.), *Les dialectes de France au Moyen Âge et aujourd'hui* (pp. 449–460). Paris: Klincksieck.

Chang, S. S., Plauché, M. C., & Ohala, J. J. (2001). Markedness and consonant confusion asymmetries. In E. Hume, & K. Johnson (Eds.), *The role of speech perception in phonology* (pp. 79–102). San Diego, London: Academic Press.

Cho, T. (2001). *Effects of prosody on articulation in English*. Ph.D. dissertation, University of California at Los Angeles, Department of Linguistics.

Cho, T., Jun, S.-A., & Ladefoged, P. (2002). Acoustic and aerodynamic correlates of Korean stops and fricatives. *Journal of Phonetics*, *30*, 193–228.

Cho, T., & Keating, P. A. (2001). Articulatory and acoustic studies of domain-initial strengthening in Korean. *Journal of Phonetics*, *29*, 155–190.

Cho, T., & McQueen, J. M. (2005). Prosodic influences on consonant production in Dutch: Effects of prosodic boundaries, phrasal accent and lexical stress. *Journal of Phonetics*, *33*, 121–157.

Cho, T., McQueen, J. M., & Cox, E. A. (2007). Prosodically driven phonetic detail in speech processing. The case of domain-initial strengthening in English. *Journal of Phonetics*, *35*, 210–243.

Corneau, C., Soquet, A., & Demolin, D. (2000). Une étude EPG de la palatalisation des occlusives velaires en français. *Actes des XXIIIèmes Journées d'Études sur la Parole* (pp. 445–448), Aussois, France.

Coustenoble, H. N. (1945). *La phonétique du provençal moderne en terre d'Arles*. Hertford: Stephen Austin and Sons.

Dixit, R. P., & Shipp, T. (1985). Study of subglottal air pressure during Hindi stop consonants. *Phonetica*, *42*, 53–64.

Docherty, G. J. (1992). *The timing of voicing in British English obstruents*. Dordrecht: Foris.

Dorman, M. F., Studdert-Kennedy, M., & Raphael, L. J. (1977). Stop-consonant recognition: Release bursts and formant transitions as functionally equivalent, context-dependent cues. *Perception and Psychophysics*, *22*, 109–122.

Dukelski, N. I. (1960). Cercetare fonetică experimentală asupra palatalizării şi a labializării consoanelor romîneşti. *Fonetică si Dialectologie*, *2*, 7–45.

Fant, G. (1960). *Acoustic theory of speech production*. The Hague: Mouton.

Farnetani, E. (1990). V-C-V lingual coarticulation and its spatio-temporal domain. In W. J. Hardcastle, & A. Marchal (Eds.), *Speech production and speech modelling* (pp. 93–110). Netherlands: Kluwer.

Farnetani, E., & Kori, S. (1986). Effects of syllable and word structure on segmental durations in spoken Italian. *Speech Communication*, *5*, 17–34.

Fontdevila, J., Pallarès, M. D., & Recasens, D. (1994). The contact index method of EPG data reduction. *Journal of Phonetics*, *22*, 141–154.

Fougeron, C. (1998). *Variations articulatoires en début de constituents prosodiques de différents niveaux en français*. Ph.D. dissertation, Université Paris III.

Fougeron, C. (2001). Articulatory properties of initial segments in several prosodic constituents in French. *Journal of Phonetics*, *29*, 109–135.

Fougeron, C., & Keating, P. A. (1997). Articulatory strengthening at edges of prosodic domains. *Journal of the Acoustical Society of America*, *101*, 3728–3740.

Gardette, P. (1967–1984). *Atlas linguistique et ethnographique du lyonnais (ALL)*, 3 Volumes. Paris: Editions du Centre Nationale de la Recherche Scientifique.

Gartner, T. (1910). *Handbuch der rätoromanischen Sprache und Literatur*. Halle: Max Niemeyer.

Gauchat, L., Jeanjaquet, J., & Tappolet, E. (1925). *Tableaux phonétiques des patois de la Suisse Romande*. Neuchâtel: Paul Attinger.

Goebl, H. (1998). *Atlant linguistich dl ladin dolomitich y di dialec vejins (ALD)*, 4 Volumes. Wiesbaden: Dr. Ludwig Reichert Verlag.

Grammont, M. (1971). *Traité de phonétique* (9th ed.). Paris: Delagrave.

Guion, S. G. (1996). *Velar palatalization: Coarticulation, perception, and sound change*. Ph.D. dissertation, University of Texas, Austin.

Guion, S. G. (1998). The role of perception in the sound change of velar palatalization. *Phonetica*, *55*, 18–52.

Haiman, J., & Benincà, P. (1992). *The Rhaeto-romance languages*. London: Routledge.

Hall, T. A., Hamann, S., & Zygis, M. (2006). The phonetic motivation for phonological stop assibilation. *Journal of the International Phonetic Association*, *36*, 59–82.

Hanson, M. H., & Stevens, K. N. (2003). Models of aspirated stops in English. In M. J. Solé, D. Recasens, & J. Romero (Eds.), *Proceedings of the 15th international congress of phonetic sciences*, Vol. I (pp. 783–786). Barcelona: Causal Productions.

Hardcastle, W., Jones, W., & Knight, C. (1989). New developments in electropalatography: A state-of the art report. *Clinical Linguistics and Phonetics*, *3*, 1–38.

Haust, J. (1953–1997). *Atlas linguistique de la Wallonie (ALW)*, Vol. 15. Liège: Vaillant-Carmanne.

Hock, H. H. (1986). *Principles of historical linguistics* (2nd ed.). Berlin: Mouton de Gruyter.

Howell, P., & Rosen, S. (1983). Production and perception of rise time in the voiceless affricate/fricative distinction. *Journal of the Acoustical Society of America*, *73*, 976–984.

Jaberg, K., & Jud, J. (1928–1935). *Sprach- und Sachatlas Italiens und der Südschweiz (AIS)*, 6 Volumes. Zofingen: Universität Zurich.

Keating, P., & Lahiri, A. (1993). Fronted velars, palatalized velars, and palatals. *Phonetica*, *50*, 73–101.

Keating, P., Wright, R., & Zhang, J. (1999). *Word-level asymmetries in consonant articulation*. UCLA Working Papers in Phonetics, Vol. 97 (pp. 157–173).

Ladefoged, P., & Bladon, A. (1982). Attempts by human speakers to reproduce Fant's nomograms. *Speech Communication*, *1*, 185–198.

Ladefoged, P., & Maddieson, I. (1996). *The sounds of the world's languages*. Oxford: Blackwell.

Lausberg, H. (1970). *Lingüística románica*. Madrid: Gredos.

Lehiste, I., & Peterson, G. E. (1959). Vowel amplitude and phonemic stress in American English. *Journal of the Acoustical Society of America*, *31*, 428–435.

Liker, M., & Gibbon, F. E. (2007). EPG characteristics of velar stops in normal adult English speakers. In J. Trouvain, & W. J. Barry (Eds.), *Proceedings of the 16th international congress of phonetic sciences*, Vol. 1 (pp. 605–608). Saarbrücken: Universität des Saarlandes.

Lisker, L., & Abramson, A. S. (1964). A cross-language study of voicing in initial stops: Acoustical measurements. *Word*, *20*, 384–422.

Lutta, C. M. (1923). *Der Dialekt von Bergün. Beiheft zur Zeitschrift für romanische Philologie*, Vol. 71. Halle: Niemeyer.

Luzi, J. (1904). Der sutselvischen Dialekte. *Romanische Forschungen*, *16*, 757–846.

Maddieson, I. (1980). *Palato-alveolar affricates in several languages*. UCLA Working Papers in Phonetics, Vol. 51 (pp.120–126).

Mair, S. J., Scully, C., & Shadle, C. H. (1996). Distinctions between [t] and [tʃ] using electropalatographic data. In *Proceedings of the international conference on spoken language processing 96* (pp. 1597–1600). Philadelphia.

Malécot, A. (1970). The lenis-fortis opposition: Its physiological parameters. *Journal of the Acoustical Society of America*, *47*, 1588–1592.

Maurand, G. (1974). *Phonétique et phonologie du parler occitan d'Ambialet* (*Tarn*). Ph.D. dissertation, Université de Toulouse.

Max, L., & Onghena, P. (1999). Some issues in the statistical analysis of completely randomized and repeated measures designs for speech, language, and hearing research. *Journal of Speech, Language and Hearing Research*, *42*, 261–270.

Nicolaidis, K. (2001). An electropalatographic study of Greek spontaneous speech. *Journal of the International Phonetic Association*, *21*, 67–86.

Ohala, J. J. (1983). The origin of sound patterns in vocal tract constraints. In P. F. MacNeilage (Ed.), *The production of speech* (pp. 189–216). New York, Heidelberg, Berlin: Springer.

Ohala, J. J. (1985). Linguistics and automatic processing of speech. In R. de Mori, & C. Y. Suen (Eds.), *New systems and architecture for automatic speech recognition and synthesis* (pp. 447–475). Berlin, Heidelberg: Springer.

Ohala, J. J. (1992). What's cognitive, what's not, in sound change. In G. Kellermann, & D. Morrisey (Eds.), *Diachrony within synchrony: Language history and cognition* (pp. 309–335). Frankfurt: Peter Lang Verlag.

Pope, M. K. (1934). *From Latin to Modern French with special consideration of Anglo-Norman*. Manchester: Manchester University Press.

Recasens, D. (1984). V-to-C coarticulation in Catalan VCV sequences: An articulatory and acoustical study. *Journal of Phonetics*, *12*, 61–73.

Recasens, D. (1986). *Estudis de fonètica experimental del català oriental central*. Barcelona: Publicacions de l'Abadia de Montserrat.

Recasens, D. (1990). The articulatory characteristics of palatal consonants. *Journal of Phonetics*, *18*, 267–280.

Recasens, D. (1996). *Fonètica descriptiva del català* (2nd ed.). Barcelona: Institut d'Estudis Catalans.

Recasens, D. (2006). Integrating coarticulation, assimilation and blending into a model of articulatory constraints. In L. Goldstein, D. Whalen, & C. Best (Eds.), *Laboratory phonology*, 8 (pp. 611–634). Berlin, New York: Mouton de Gruyter.

Recasens, D., & Espinosa, A. (2006). Articulatory, positional and contextual characteristics of palatal consonants. Evidence from Majorcan Catalan. *Journal of Phonetics*, *34*, 295–318.

Recasens, D., & Pallarès, M. D. (2001). *De la fonètica a la fonologia*. Barcelona: Ariel.

Reddy, N. (1981). Place of articulation of velar plosives. *Work in progress*, Vol. 14. Department of Linguistics at Edinburgh University (pp. 133–138).

Repp, B. (1984). Closure duration and release burst amplitude cues to stop consonant manner and place of articulation. *Language and Speech*, *27*, 245–254.

Repp, B. H., Liberman, A. M., Eccardt, T., & Pesetsky, D. (1978). Perceptual integration of acoustic cues for stop, fricative, and affricate manner. *Journal of Experimental Psychology*, *4*, 621–637.

Repp, B. H., & Lin, H.-B. (1989). Acoustic properties and perception of stop consonant release transients. *Journal of the Acoustical Society of America*, *85*, 379–396.

Rohlfs, G. (1966). *Grammatica storica della lingua italiana e dei suoi dialetti*, Vol. 1. Turin: Einaudi.

Rousselot, J.-P. (1924–1925). *Principes de phonétique expérimentale*. Paris, Leipzig: Welter.

Salvioni, C. (1901). La risoluzione palatina di K e G nelle Alpi Lombardi. *Studj di Filologia Romanza*, *8*, 1–34.

Scripture, E. W. (1902). *The elements of experimental phonetics*. New York: Charles Scribner's Sons.

Solé, M. J. (2007). Controlled and mechanical properties in speech. A review of the literature. In M. J. Solé, P. S. Beddor, & M. Ohala (Eds.), *Experimental approaches to phonology* (pp. 302–321). Oxford: Oxford University Press.

Stevens, K. N. (1998). *Acoustic phonetics*. Cambridge, MA: MIT Press.

Straka, G. (1965). Naissance et disparition des consonnes palatales dans l'évolution du latin au français. *Travaux de Linguistique et de Littérature Romane, Université de Strasbourg*, *3*, 117–167.

Trudgill, P. (2003). Modern Greek dialects. A preliminary classification. *Journal of Greek Linguistics*, *4*, 45–64.

Veny, J. (1983). *Els parlars catalans*. Palma, Majorca: Editorial Moll.

Winitz, H., Scheib, M. E., & Reeds, J. A. (1972). Identification of stops and vowels for the burst portion of /p, t, k/ isolated from conversational speech. *Journal of the Acoustical Society of America*, *51*, 1309–1317.

Zue, V. (1980). *Acoustic characteristics of stop consonants: A controlled study*. Bloomington: Indiana Linguistics Club.

Zygis, M., Recasens, D., & Espinosa, A. (2008). Acoustic characteristics for velar stops and velar softening in German, Polish and Catalan. In R. Sock, S. Fuchs, Y. Laprie (Eds.), *Proceedings of the eighth international seminar on speech production 2008* (pp. 97–100), Strasbourg.