Available online at www.sciencedirect.com

SCIENCE DIRECT®

Speech Communication 48 (2006) 645–666

SPEECH COMMUNICATION

www.elsevier.com/locate/specom

Dispersion and variability of Catalan vowels

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

[a] *Phonetics Laboratory, Institut d'Estudis Catalans, c/Carme, 47, 08001 Barcelona, Spain*
[b] *Department of Catalan Philology, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain*

Received 10 January 2005; received in revised form 26 September 2005; accepted 27 September 2005

Abstract

Formant frequency data for Catalan vowels reveal essentially the same degree of expansion for three dialect systems with seven vowels (Valencian, Eastern Catalan, Western Catalan). A slightly larger vowel space dispersion for a fourth system with those same vowels and stressed /ə/ (Majorcan) is not clearly associated with a larger vowel system size but rather with a local effect of schwa in repelling neighbouring vowels or with specific requirements on the production of some peripheral vowels. Schwa appears to be targetless or specified for a widely defined mid central target. Intervocalic distances were found to vary according to dialect and to vowel pair, and to compensate with each other such that the maximal formant frequency range between point vowels is kept constant across dialects. These findings are partially in support of the Adaptive Dispersion Theory, i.e., they are in agreement with the claim that vowel system expansion should be proportional to vowel system size but not with the notion that adjacent vowels should be evenly spaced in identical vowel systems. Patterns of vowel variability differ depending on the contextual or non-contextual factors involved, i.e., $F1$ shows more contextual and token-to-token variation for open vs. close vowels, while $F2$ exhibits little contextual variation and much token-dependent variation for /i/ and the opposite trend for /u/ and /ə/. These patterns are accounted for assuming that random variability for vowels is ruled by the precision involved in achieving a specific articulatory target, and that contextual variability is determined by the vowel articulatory requirements and by the relative compatibility between the articulatory gestures for adjacent vowels and consonants.

Keywords: Vowels; Catalan; Schwa; Vowel spaces; Contextual and non-contextual variability for vowels; Acoustic analysis; Electropalatography

1. Introduction

The purpose of this study is to investigate whether the size and nature of vowel inventories affect the range, distribution and degree of variability for vowels in vowel spaces. It also deals with general principles underlying the patterns of contextual and non-contextual variability for vowels. These research issues will be analyzed using a large data sample collected from 20 speakers of 4 Catalan dialects. Catalan is a Romance language spoken by about 6 million speakers in Eastern Spain. It is composed of four main dialects located in Catalonia (Eastern Catalan and Western Catalan), in the Valencia region (Valencian), and in Majorca and

* Corresponding author. Tel.: +34 3 4578183.
E-mail address: daniel.recasens@uab.es (D. Recasens).

0167-6393/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.specom.2005.09.011

the other Balearic islands (Majorcan). All four dialects share the same vowel system, i.e., /i, e, ɛ, a, ɔ, o, u/, and Majorcan Catalan has the additional vowel phoneme /ə/.

1.1. Acoustic ranges and distances in vowel spaces

The Adaptive Dispersion Theory makes two significant predictions regarding vowel dispersion in vowel systems. A prediction on vowel space dispersion states that the frequency range between point vowels ought to keep a positive relationship with vowel system size, i.e., the maximal range between peripheral vowels should increase with an increase in the number of vowels in the vowel inventory (Liljencrants and Lindblom, 1972). Moreover, an increase in the number of vowels should not only cause the distance between point vowels to increase but also the overall vowel system to expand (Bradlow et al., 1996). Another prediction is related to distinctiveness of individual contrasts. It predicts that adjacent vowels ought to be roughly equidistant in identical vowel systems while becoming less distinct as the number of vowels in the vowel inventory becomes larger (Flemming, 2002).

Studies from the literature provide contradictory evidence for the vowel space dispersion hypothesis. A trend for larger vowel inventories such as German (14 vowels) and American English (11) to display a more peripheral vowel location than smaller vowel inventories such as Greek (5) has been reported to occur for point vowels /i, a, u/ (Jongman et al., 1989). Other studies have found this relationship not to hold however. Thus, it has been pointed out that the area of the $F1 \times F2$ space covered by /i, e, a, o/ may be roughly the same in English, Spanish and Greek in spite of the fact that the former language has 11 vowel contrasts while the two latter ones have 5 vowels (Bradlow, 1995). Moreover, a comparison among 28 vowel systems of different sizes indicates that the distance between point vowels does not increase unless the language under analysis has more than 8 vowels or so (Livjn, 2000). Vowel dispersion appears to depend on speech intelligibility (Bradlow et al., 1996; Moon and Lindblom, 1994) and lexical difficulty (Munson and Solomon, 2004) rather than on vowel system size.

There is also some evidence from the literature that the acoustic distance between adjacent vowels does not keep a strict relationship with vowel system size which renders a strong version of the Adaptive Dispersion Theory dubious.

A possible outcome is for languages with different vowel system sizes to exhibit similar formant frequency intervals between adjacent vowels (rather than for larger systems to exhibit shorter distances than less crowded ones). An interesting scenario occurs when all vowels in one language are shifted towards the same $F1 \times F2$ region with respect to the vowels of another language such that the two languages may be said to differ in base of articulation. Some support for this possibility comes from data indicating that, while $F2$ of the vowels /i, e, o, u/ varies in the progression English > Spanish > Greek, the $F2$ distance between them is highly similar in all three languages (Bradlow, 1995).

Contrary to the intervowel distance hypothesis, the acoustic contrast between two adjacent vowels may be larger or smaller due to historical or phonological reasons rather than to the number of vowel phonemes in the language. This may be so since a given vowel may exhibit quite different formant frequencies in two languages. A clear example occurs in the five-vowel systems of Japanese and Spanish: a more anterior location for /u/ in Japanese than in Spanish causes the /i-u/ distance to be shorter in the former language vs. the latter (Papçun, 1976; Keating and Huffman, 1984). Also, the acoustic difference between /i/ and /y/ may be larger in German than in Swedish since /y/ is especially low in the former language, and (mid) high and (mid) low vowels may differ in height in the seven-vowel systems of Italian and Yoruba (Disner, 1983). Acoustic differences for specific vowels have also been reported to occur between dialects of a given language (see Godínez, 1978 for Spanish and Koopmans-van Beinum, 1973 for Dutch).

Within this theoretical framework, this paper will test the two hypotheses presented above for the vowel systems of four Catalan dialects, i.e., Eastern, Western, Majorcan and Valencian, sharing essentially the same basic seven vowel phonemes /i, e, ɛ, a, ɔ, o, u/. The expected outcome is that all four Catalan dialects should show comparable degrees of vowel system expansion, and similar acoustic distances between point vowels (i.e., /i, a, u/) and between adjacent vowels (e.g., /i-e/, /e-ɛ/, /ɛ-a/ and so on). In case that dialects differ with respect to vowel spacing, it is worth investigating whether these differences should be attributed to base of articulation or to the location of specific vowels within the vowel space. In testing the Adaptive Dispersion Theory, it should be kept in mind that vowel contrasts ought to be better specified by $F1$, a major correlate of articulatory opening and intensity, rather than by $F2$ which is related mainly to tongue fronting and rounding (Lindblom, 1986).

There is some evidence for dialect-dependent differences in mid and low vowel production in Catalan. Thus, preliminary data suggest that mid vowels are more open and /a/ is more close and more anterior in Majorcan and Valencian than in Eastern Catalan (Recasens, 1986; Herrick, 2003). If those phonetic characteristics turn out to be true, distances between mid low /ɛ, ɔ/ and low /a/ are expected to be smaller in the two former dialects than in the latter which runs against the hypothesis that adjacent vowels should be evenly spaced in vowel systems with the same number of vowels. Considering these possible dialect-dependent differences, a less strict version of the Adaptive Dispersion Theory will be tested for the Catalan dialects in question, i.e., whether distances between adjacent vowels tend to compensate with each other such that the overall range across vowel systems is kept constant. If this hypothesis is correct, a decrease in the formant frequency distance between the members of one or more pairs of adjacent vowels ought to be compensated by an increase in the formant frequency distance between adjacent vowels in other vowel pairs within the same vowel system.

1.2. The role of /ə/

The four Catalan dialects under analysis exhibit the same number of peripheral vowels but differ regarding the number of central vowels. Thus, in contrast with Eastern Catalan, Western Catalan and Valencian, Majorcan has the additional vowel /ə/ and thus, eight rather than seven vowel phonemes. The vowel in question may appear not only in unstressed syllables but also in stressed syllables, and allows differentiating minimal pairs. Schwa also occurs in Eastern Catalan but in unstressed position only.

This scenario allows us to investigate whether the presence of a central vowel causes the vowel system to expand. There is a view stating that schwa is a parallel vowel to peripheral non-central vowels such that its presence or absence should not modify the vowel system structure (Schwartz et al., 1997). According to this view, schwa should be considered a targetless vowel resulting from the articulatory reduction of peripheral vowels. Indeed, it has been hypothesized that unstressed schwa has no articulatory target in English, Dutch and Eastern Catalan based on the observation that its formant frequencies show much variability as a function of neighbouring consonants and vowels (Magen, 1989; Bates, 1995; Kondo, 1994; Koopmans-van Beinum, 1994; Van Bergem, 1994; Recasens, 1985). However, the fact that acoustic variability affects $F2$ rather than $F1$ could be indicative that schwa is specified for height (i.e., as a mid vowel) but not for fronting. Other X-ray, microbeam, MRI and formant frequency data suggest that English unstressed /ə/ is not targetless but involves the formation of a back constriction at the upper or entire pharynx (Gick, 1999:43; Gick et al., 2002; Browman and Goldstein, 1992; McDougall, 2003).

In the light of this conflicting evidence, the present paper will investigate whether Majorcan /ə/ is specified for an articulatory or acoustic target or may be considered a targetless vowel. In the latter event, the vowel should be highly variable and roughly equidistant from peripheral vowels, and play no role in vowel system expansion. In the former event, /ə/ is expected to approach a specific peripheral region of the vowel space, not to vary a great deal, and play some role in vowel dispersion by repelling those vowels that lie close to it.

In determining the position and the degree of variability for /ə/, we should pay attention to the fact that Majorcan Catalan schwa may show up both in stressed and unstressed position. In the present study, we will compare the location and variability of stressed /ə/ in Majorcan and of unstressed /ə/ in Majorcan and Eastern Catalan. The finding that schwa is a highly variable central vowel in both stress positions would be in support of the targetless nature of stressed /ə/. This outcome would match the situation in English where stressed /ɜ/ in bird ($F1 = 500$ Hz, $F2 = 1350$–1400 Hz) resembles unstressed /ə/ in again and is less open and more centralized than stressed /ʌ/ in cut ($F1 = 650$ Hz, $F2 = 1200$ Hz) (Peterson and Barney, 1952; Hillenbrand et al., 1995). It would also be in agreement with data from Bulgarian indicating that stressed and unstressed /ə/ exhibit an $F1$ frequency halfway between mid front and mid back vowels and a similar $F2$ frequency to /a/ (Wood and Petterson, 1988: 253; Christov, 1987). The alternative possibility is for unstressed schwa to be a central vowel, and for stressed schwa to be characterized as a mid back unrounded vowel involving active tongue body retraction and perhaps the formation of a narrower pharyngeal constriction.

1.3. Variability

Along with the vowel system expansion and intervowel distance hypotheses presented above, vowel variability may also be influenced by vowel system size (Section 1.3.1 below). Extensive formant frequency data recorded in the present paper, i.e., 7 or 8 vowels, 4 contexts, 7 repetitions and 20 speakers, also allow testing whether vowels vary in a similar or different fashion as a function of segmental context (Section 1.3.2) and of non-contextual factors such as vowel token and speaker (Section 1.3.3).

1.3.1. Vowel system size

According to the Adaptive Dispersion Theory, variability for individual vowels should be inversely related to the number of phonemes in the vowel inventory, i.e., vowel formant values should vary to a larger extent in small than in large systems (Lindblom, 1986). This hypothesis has both been confirmed (Manuel, 1990 for African languages) and disconfirmed (Bradlow, 1995 for English and Spanish). Moreover, it has been found that specific vowels may exhibit different degrees of variability in identical vowel systems (see Koopmans-van Beinum, 1973 for two Dutch dialects).

If the hypothesis under discussion is correct, vowels are expected to be subject to similar degrees of variability in all four Catalan dialects. This prediction should also apply to Majorcan if schwa is targetless. Otherwise, variability ought to be less for vowels placed close to schwa than for those located far away from it, namely, for mid vowels than for high and low vowels (if schwa is mid central) or else for mid back vowels than for other vowels (if /ə/ involves a pharyngeal constriction).

1.3.2. Contextual variability

Contextual variation in vowels appears to be conditioned by the relative compatibility between the articulatory gestures for adjacent vowels and consonants, and conforms to similar patterns in different languages (see data for Catalan and English in Recasens, 1985; Stevens and House, 1963; Hillenbrand et al., 2001). Moreover, the degree to which vowels allow contextual effects to occur depends on the articulatory requirements during their production and usually increases at tongue regions not participating in constriction formation (Recasens, 1999). In agreement with previous studies (Bradlow, 1995; Pisoni, 1980), this view disconfirms the claim made by the Quantal Theory that acoustic stability ought to differ according to whether vowels are /i, a, u/ or not (Stevens, 1989; Perkell and Nelson, 1983; Perkell, 1990).

Data on C-to-V effects for Catalan reveal more $F1$ variability for open vs. close vowels and for mid front vs. mid back vowels, less $F2$ variability for /i/ than for mid front and low vowels, and a high degree of $F2$ variability for back rounded vowels more so if high than mid. A similar scenario applies to English though low vowels and /ʌ/ exhibit a low degree of $F2$ variability in this case. Articulatory studies also report less contextual variability for /i/ than for /a, u/ at the tongue dorsum (Hoole et al., 1990 for German). As pointed out in Section 1.2 above, schwa is expected to be highly variable along all formant dimensions.

Much coarticulatory resistance for /i/ (and for other front vowels) may be associated with the high articulatory requirements involved in raising and fronting the tongue dorsum towards the palate. C-to-V effects on the high front vowel affect the degree of constriction at the palatal place of articulation, and are triggered by consonants produced with a low predorsum and more or less postdorsum retraction, i.e., dark /l/, trill /r/, /w/. Lip closing for labials may also cause $F2$ lowering for /i/ to occur. On the other hand, a high degree of $F2$ variability for back rounded vowels, /a/ and schwa is associated with tongue predorsum raising and tongue postdorsum fronting (and also with lip unrounding in the case of /ɔ, o, u/) exerted by palatal and dentoalveolar consonants. Different degrees of $F1$ variation for open vs. close vowels are in agreement with differences in coarticulatory sensitivity in jaw height and in tongue predorsum activity (Keating et al., 1994). Those vowel-dependent differences in $F1$ variability are caused by consonants differing in jaw and tongue dorsum height, i.e., dark /l/ and trill /r/ (lower jaw and tongue dorsum position) vs. palatals (higher jaw and tongue dorsum).

1.3.3. Non-contextual variability

Several studies in the literature have dealt with vowel variability as a function of token and speaker. In order to measure token-to-token variation, context and speaker need to be kept constant, e.g., Pisoni (1980) where vowel variability was computed across repetitions of English /hVd/ words for a given speaker. On the other hand, speaker-dependent vowel variability can only be evaluated provided that we compare single numerical values for each speaker, e.g., see Pols et al. (1973), Koopmans-van Beinum (1973) and Bradlow (1995) where cross-speaker vowel variability was measured for a single repetition or for the mean across repetitions of a given CVC sequence.

Studies on non-contextual variability patterns report more *F*1 variation for open vs. close vowels and more *F*2 variation for front vs. low and back rounded vowels. There appear to be language-dependent trends in this respect. Thus, the degree of non-contextual *F*2 variability for /u/ may match that for /i/ in Spanish (Bradlow, 1995), and /u/ turns out to be more variable than all other vowels in Japanese (Keating and Huffman, 1984). These findings challenge the predictions of the Quantal Theory in so far as point vowels fail to exhibit similar degrees of non-contextual variability in *F*2 frequency. They suggest instead that the degree of non-contextual variability depends inversely on the precision involved in achieving a specific vowel articulatory configuration in a given contextual condition. Thus, the fact that /i/ is specified for a low degree of *F*1 variability and a high degree of *F*2 variability may mean that speakers are more accurate in raising the tongue dorsum than in forming a precise dorsopalatal constriction during this vowel production. Also, a low degree of non-contextual variability for back rounded vowels may be due to the fact that speakers are quite precise in combining the lip rounding and dorsovelar constriction gestures for the vowels in question.

In the light of evidence from the literature, the present study will test whether contextual and non-contextual factors cause different patterns of vowel variability to occur. Thus, we expect *F*1 variability to change inversely with vowel height as a general rule, and *F*2 for high vowels to vary more or less depending on whether variability is associated with contextual factors (maximal for /u/, minimal for /i/) or with non-contexual factors (minimal for /u/, maximal for /i/).

2. Method

2.1. Data recordings

2.1.1. Experiment 1

The Catalan vowels /i, e, ɛ, a, ɔ, o, u/ and the Majorcan Catalan vowel /ə/ were read seven times in stressed position in the meaningful sentences listed in Table 1. Vowels were preceded and followed by consonants agreeing in place of articulation, i.e., labials (involving lip closing or approximation and no active lingual activity), dentoalveolars (produced with an apical or laminal closure or constriction and moderate tongue dorsum raising), palatals (articulated with much tongue dorsum raising towards the hard palate), and dark /l/ and the trill /r/ (specified for some apicoalveolar central contact and some predorsum lowering and postdorsum retraction). Catalan dialects do not differ regarding the articulatory implementation of the consonants in question except for /l/ which is less dark in Valencian than in the other Catalan dialects (Recasens and Espinosa, 2005). The absence of specific Catalan words may render the CVC sequences in Table 1 not perfectly symmetrical regarding place of articulation. Thus, labiovelar /w/ may act as a contextual consonant in the labial condition, and the consonant preceding or following the target vowel may be /t/ or /s/ in the palatal and /l, r/ conditions.

Five native speakers of each of the four Catalan dialects under investigation were asked to read all 32 sentences as naturally as possible at a comfortable rate. All 20 speakers were male, about 25–45 years of age, and born and presently living in their respective dialectal region. Throughout the paper the four dialects will be referred to as MC (Majorcan), VC (Valencian), WC (Western Catalan) and EC (Eastern Catalan), and speakers will be identified with the initials AR, BM, MJ, ND, CA (Majorcan), VB, JM, MS, VG, AV (Valencian), MQ, PR, AL, AG, GR (Western Catalan) and DR, DP, JC, JO, PJ (Eastern Catalan). Speaker DR is the first author of this paper.

Speakers of Catalan dialects exhibiting relevant vowel formant frequency differences according to literature sources (see Section 1), i.e., all Majorcan and Valencian speakers and the Eastern Catalan speakers DR, DP and JC, recorded the acoustic signal simultaneously with linguopalatal contact data using the Reading EPG-3 system (Hardcastle et al., 1989). Tongue contact data allowed determining whether possible dialect-dependent differences in the vowel formant frequencies are matched by differences in vowel articulation. This articulatory-acoustic relationship should be more reliable for front vowels than for low and back vowels since the former are produced with more dorsal contact than the latter. Linguopalatal contact configurations were collected with 62 electrode artificial palates every 10 ms and the acoustic data were sampled at 10 kHz. Recordings started after some training to ensure that speakers felt comfortable

Table 1
Catalan sentences with words including the stressed vowels subject to analysis

Labial context			
/i/	Encén la p**i**pa	[ˈpipə]	"Light on the pipe"
/e/	Crec que té f**e**bre	[ˈfeßɾə]	"I think he/she has a fever"
/ɛ/	Té mal al p**e**u	[pɛw]	"His/her foot aches"
/a/	Li cau la b**a**va	[ˈbaßə]	"He/she is drooling"
/ɔ/	Es fa la p**o**bra	[ˈpɔßɾə]	"He/she pretends to be poor"
/o/	La proa i la p**o**pa	[ˈpopə]	"The bow and the stern"
/u/	La cuina no b**u**fa	[ˈbufə]	"The kitchen is not working"
/ə/	Posem-hi p**e**bre	[ˈpəßɾə]	"Let us add some pepper"
Dentoalveolar context			
/i/	Ves a la c**i**ta	[ˈsitə]	"Turn up for the appointment"
/e/	Ha romput el t**e**st	[test]	"He/she has broken the flowerpot"
/ɛ/	D'anys en té s**e**t	[sɛt]	"He/she is seven years old"
/a/	Beu-te la t**a**ssa	[ˈtasə]	"Drink what is in the cup"
/ɔ/	Caigué dins d'un s**o**t	[ˈsɔt]	"It fell inside a hole"
/o/	El pis de s**o**ta	[ˈsotə]	"The downstairs floor"
/u/	L'han ben fot**u**da	[ˈfutuðə]	"They have really harmed her"
/ə/	És petit**e**ta	[pətiˈtətə]	"She is very small"
Palatal context			
/i/	Ven la motx**i**lla	[muˈtʃiʎə]	"Sell the rucksack"
/e/	Una cosa molt ll**e**tja	[ˈʎedʒə]	"A very ugly thing"
/ɛ/	Ell recull **e**stris	[rəkuˈʎɛstɾis]	"He picks up the tools"
/a/	Això no enll**a**ça	[ənˈʎasə]	"This does not work"
/o/	Actua la Ll**o**ll	[ʎoʎ]	"Lloll[a] is acting"
/ɔ/	Ven a la ll**o**tja	[ˈʎɔdʒə]	"She/he sells at the market"
/u/	En Ramon Ll**u**ll	[ʎuʎ]	"Ramon Llull[b]"
/ə/	Compleix la ll**e**i	[ʎəj]	"He/she obeys the law"
/l, r/ context			
/i/	Sempre pren t**i**l.la	[ˈtilə]	"He/she always drinks herbal tea"
/e/	Encén la t**e**le	[ˈtele]	"Switch the TV on"
/ɛ/	Mira el c**e**l	[sɛl]	"Look at the sky"
/a/	Neteja la s**a**la	[ˈsalə]	"Clean up the hall"
/ɔ/	No estiguis s**o**la	[ˈsɔlə]	"Do not be alone"
/o/	Compra't la t**o**rre	[ˈtorə]	"Buy the tower"
/u/	Així ho tit**u**la	[tiˈtulə]	"He/she gives it this name"
/ə/	És bona t**e**la	[ˈtələ]	"It is a good fabric"

Words are presented in orthographic notation and in Eastern Catalan phonetic transcription (except for words with stressed /ə/ which occur in Majorcan only). The English translation is also given.
[a] Name of a Catalan actress.
[b] Name of a Catalan philosopher.

with the artificial palate in place. The artificial palates were thin (i.e., about 1.5 mm thick) and therefore, should not have caused a significant oral cavity reduction which could affect the formant frequency values for the vowels under study.

2.1.2. Experiment 2

In order to gather information about the phonetic specification and the degree of contextual variability for stressed and unstressed /ə/, we analyzed some additional speech material recorded at Haskins Laboratories (New Haven, USA) and in Majorca in 1984.

Data included three repetitions of unstressed /ə/ in nonsense symmetrical /Cəˈ Ca/ sequences uttered by three male speakers of Eastern Catalan (DR, BI, GO), and of stressed and unstressed /ə/ in nonsense symmetrical /ˈCəCa/ and /CəˈCa/ sequences produced by three Majorcan Catalan males (AD, RI, CO). Consonants were grouped into the following seven articulatory types: labials (/p, b, f/); dentoalveolars (/t, d, s, z/); palatals (/tʃ, dʒ, ʃ, ʒ, ʎ, j/); velars (/k, g/); labiovelars (/w/); the trill /r/; dark /l/. The number of tokens was 63 in Eastern Catalan (1 stress condition × 7 consonant contexts × 3 repetitions × 3 speakers) and 98 in Majorcan (2 stress conditions × 7 consonant contexts × 2 or 3 repetitions depending on speaker × 3 speakers). Sequences were embedded in the carrier sentence 'digues __ així' ("say ___ so").

Those speakers also recorded the seven stressed vowels /i, e, ɛ, a, ɔ, o, u/ in the same contextual conditions (Eastern Catalan), and in the context /sVk/ in meaningful Catalan words (Majorcan Catalan), using the same carrier sentence.

2.2. Data analysis

2.2.1. Experiment 1

(a) The acoustic data for the Experiment 1 speech material were filtered at 4.8 kHz and processed with the Computerized Speech Lab (CSL) analysis system of Kay Elemetrics. Overall, 4060 vowel realizations were analyzed, i.e., 7 vowels × 4 consonant contexts × 7 repetitions × 15 speakers (VC, WC, EC), 8 vowels × 4 consonant contexts × 7 repetitions × 5 speakers (MC). Frequency values were measured for the first three formants ($F1, F2, F3$) at the vowel midpoint placing a cursor in the middle of the formant on spectrographic displays. Spectral peaks were checked on LPC spectral displays whenever spectrographic readings were not reliable enough. Vowel boundaries were taken to occur at the onset and offset of the vowel formants following and preceding the closure period for stops, the frication period for fricatives, and the low intensity formants for approximants and laterals. Segmentation criteria for contextual stops and fricatives were used for contextual affricates. Vowel offset before /r/ was taken to occur just before the first short closure period for the trill.

EPG data processing was carried out on linguopalatal contact configurations such as those represented in Fig. 1. Tongue contact takes place on eight rows of electrodes, i.e., from frontmost row 1 placed at the top of those configurations through backmost row 8 at the bottom. In the figure, electrodes may appear in black (80–100% electrode activation across repetitions), grey (40–80% activation) and white (less than 40% activation). For the purpose of the present study, the artificial palate was subdivided into two articulatory zones, i.e., alveolar (4 front rows) and palatal (4 back rows).

The contact index Q_p, i.e., quotient of dorsopalatal contact, was computed for all vowels averaging all contacted electrodes at the 4 back rows by the total amount of 32 electrodes and rescaling the resulting value so that a range from 0 to 1 was obtained. In order to find out whether contact configurations were influenced by speaker-dependent differences in palate shape, maximal palate height was measured at the back rows 7 and 8 for all thirteen artificial palates.

Formant frequency data were submitted to a speaker normalization procedure in order to compare vowel formant frequencies across dialects. This transformation was carried out because it is known that absolute formant frequency values are influenced by individual differences in the speaker's vocal anatomy. Failure to apply a speaker normalization transformation renders cross-dialect comparisons of dubious validity. The normalization method proposed by Nearey (1978), i.e., CLIH or Constant Logarithm Interval Hypothesis, was judged to be most appropriate for the present data set. This method has been characterized as

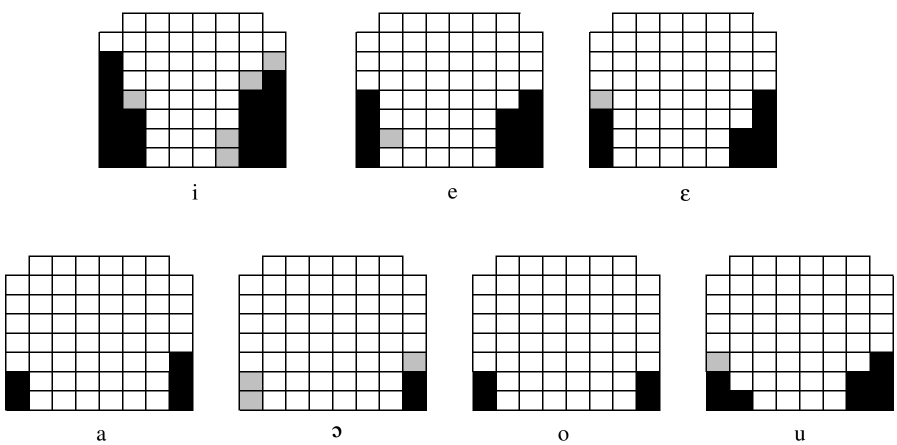

Fig. 1. Linguopalatal contact configurations for Catalan vowels in the palatal context condition according to the Valencian speaker AV. See text for details.

vowel-extrinsic since it uses acoustic information distributed across more than one vowel category of a given speaker, i.e., the overall mean formant frequencies across all vowels for that speaker, as a correction factor for the frequencies of the individual vowels. It is also formant-intrinsic since the transformed dimensions refer to one formant rather than to several formants. Nearey's method has been found to perform better than other methods in reducing the anatomical/physiological variation while preserving sociolinguistic variation (Adank, 2003). A possible problem, namely, that the value of the correction factor should depend on the number of vowels in the vowel system, does not apply to our present case since all four Catalan dialects exhibit essentially the same vowel phonemes. Moreover, the presence of schwa in Majorcan should have little effect on the normalization procedure since this vowel is located near the center of the vowel space.

Normalization was performed on data for all vowel repetitions and for each speaker. The normalization formula is CLIH $= F^*_{N[V]s} = G_{N[V]s} - G_{.[.]s}$, where $F^*_{N[V]s}$ is the measurement in Hz of the Nth formant of vowel V for subject s, and G stands for natural logarithm. According to the formula, the natural logarithm of the mean formant frequency across vowels was subtracted from the natural logarithm of the formant frequencies for the individual vowels. Normalized vowel formant frequencies for each speaker were obtained averaging the normalized formant frequencies for all vowel repetitions, and those for each dialect by normalizing vowel formant frequency means across repetitions, contexts and speakers.

Dialect-dependent differences in formant frequency for Catalan vowels were assessed by applying one-way ANOVAs to the normalized vowel data with 'dialect' (MC, VC, EC, WC) as the independent variable. The number of ANOVAs was 14 (2 formants × 7 vowels). Each ANOVA was run on 80 frequency values (4 consonant contexts × 5 speakers × 4 dialects). The significance level was fixed at $p < 0.05$. Bonferroni multiple comparisons tests were carried out on data yielding a main effect of 'dialect' in order to ascertain significant vowel formant frequency differences for all pairs of dialects.

Articulatory-acoustic correlations were carried out between Q_p and the unnormalized $F1$ and $F2$ data so as to find out whether dorsopalatal contact changes directly with $F2$ frequency and inversely with $F1$ frequency (Fant, 1960). Q_p-$F1$ and Q_p-$F2$ correlations involved 96 comparisons, i.e., 8 vowels × 5 MC speakers + 7 vowels × 5 VC speakers + 7 vowels × 3 EC speakers.

(b) Dialect-dependent differences in vowel space dispersion were estimated for each dialect and for each speaker using two measures, i.e., mean Euclidean distance and maximal $F1$ and $F2$ ranges.

Mean Euclidean distances were obtained for the unnormalized and normalized data by averaging the $F1$ and $F2$ frequency distances between all seven peripheral vowels and the 'centroid' or grand mean across the $F1$ and $F2$ values for all vowels. In order to allow for maximal within-vowel dispersion, the mean Euclidean distance for each dialect was derived from 28 distances between the four contextual means for each vowel and the centroid. This procedure is analogous to the one used in Bradlow et al. (1996) where the mean Euclidean distance was calculated using six contextual distances for each vowel. One-way and two-way ANOVAs at the $p < 0.05$ significance level were performed on Euclidean distance values for all contextual conditions, speakers and dialects with 'dialect', and with 'dialect' and 'context', as the independent variables (80 values = 4 contexts × 5 speakers × 4 dialects).

As shown by Lindblom and colleagues (Moon and Lindblom, 1994), vowel formant frequencies and thus, vowel space dispersion, may be proportional to vowel duration. Regarding our study, this means that dialectal differences in overall vowel dispersion could be related to dialect-dependent differences in vowel duration arising perhaps from variations in speech rate. In order to ascertain this relationship, we averaged all vowels' durations for each individual speaker and correlated the resulting means for all 20 speakers with the corresponding mean Euclidean distances. Data for Majorcan /ə/ were excluded from the averaging procedure. Correlation analyses involved 20 pairs of values (one for each speaker), and were performed on the unnormalized and normalized dispersion data.

Maximal $F1$ and $F2$ ranges for each speaker and for each dialect were determined by the highest and lowest attested $F1$ and $F2$ frequency values, i.e., between the tokens exhibiting a minimal $F1$ for /i/ and a maximal $F1$ for /a/ and between the tokens showing the highest $F2$ for /i/ and the lowest $F2$ for /u/. Analogous differences were also computed between the mean vowel formant frequencies across repetitions for each speaker and across speakers for each dialect.

The acoustic intervals between adjacent vowels were evaluated separately for each dialect using normalized formant frequency values. Thus, *F*1, *F*2 and Euclidean distances were obtained for pairs of vowels differing in height and fronting, respectively, i.e., /i-e/, /e-ɛ/, /ɛ-a/, /a-ɔ/, /ɔ-o/ and /o-u/ (*F*1, Euclidean) and /i-u/, /e-o/ and /ɛ-ɔ/ (*F*2, Euclidean). Intervowel intervals were not measured for the unnormalized formant frequencies since the Euclidean distance computation would have assigned much more weight to *F*2 than to *F*1.

(c) The degree of context-dependent, token-to-token and speaker-dependent variability was evaluated for the unnormalized *F*1 and *F*2 data for each vowel.

Contextual variability was measured as a function of speaker and dialect, and across dialects. We calculated the standard deviations over the contextual means across repetitions for each speaker (speaker-dependent contextual variability), the speaker-dependent means for each contextual condition and the standard deviations over the contextual means (dialect-dependent contextual variability), and the dialect-dependent means for each context and the standard deviations over the four resulting means (contextual variability across dialects). Context-dependent variability for stressed /ə/ was not processed for the latter condition since this vowel is only available in Majorcan Catalan.

In order to analyze token-to-token variability, we calculated the standard deviation values across the seven repetitions of a given vowel in each consonant context for each speaker. Speaker-dependent variability was expressed by standard deviations over the 20 speakers' means across repetitions of each vowel in each consonant context.

2.2.2. Experiment 2

The speech material described in Section 2.1.2 were digitized at 10 kHz after preemphasis and low pass filtering. Spectral analysis was carried out using linear prediction coding (LPC) with the Interactive Laboratory System package at Haskins Laboratories in 1984. The vowel segmentation procedure was identical to the one described in Section 2.2.1 above. *F*1, *F*2 and *F*3 values were measured at the vowel (quasi)steady-state period or at the vowel midpoint if a steady state was absent.

In order to determine whether stressed and unstressed /ə/ were different or not, a two-way ANOVA was applied to *F*1 and *F*2 data for all repetitions of Majorcan Catalan /ə/. The independent variables were 'stress' (stressed, unstressed) and 'consonant context' (labial, dentoalveolar, palatal, velar, labiovelar, /r/, /l/), and the significance level was fixed at $p < 0.05$. The number of values subject to statistical test was 98 for each formant (see Section 2.1.2 above).

3. Results

3.1. Articulatory and acoustic vowel characteristics

3.1.1. Formant frequency

Fig. 2 shows unnormalized (top) and normalized (bottom) $F1 \times F2$ frequency plots for the MC, VC, WC and EC vowels. Unnormalized formant frequencies correspond to averages across repetitions, contextual conditions and speakers for each vowel and dialect. Normalized values were obtained by applying Nearey's formula to these averages. Table 2 reports unnormalized data for the individual speakers, and Table 3 the corresponding normalized values.

A comparison between the two $F1 \times F2$ plots in the figure shows that, as expected, dialect-dependent differences for most vowels diminish in the normalized vs. unnormalized condition. ANOVAs run on the normalized *F*1 frequencies yielded a significant effect of dialect for the vowels /i, a, ɔ, u/ ($F(3,76) = 5.98$, $p < 0.001$; $F(3,76) = 3.85$, $p < 0.013$; $F(3,76) = 11.66$, $p < 0.001$; $F(3,76) = 3.34$, $p < 0.024$). A non-significant effect of dialect was obtained for the *F*2 data for all vowels.

Results for the Bonferroni multiple comparisons tests presented in Table 4 agree with the size of the mean *F*1 differences in Fig. 2 and with impressionisic observations reported in the literature (see Section 1). Relevant significant dialect-dependent differences affect *F*1 for low and mid low vowels. Thus, this formant turned out to be lower in MC and VC than in EC in the case of /a/, and higher in MC vs. WC, EC and in VC vs. WC in the case of /ɔ/. High vowels appear to be specially close in MC, as shown by significant *F*1 differences for /i/ (WC, EC > MC) and /u/ (EC > MC). In summary, /a/ has a specially close realization, and mid low back /ɔ/ is specially open, in MC and, less so, in VC; moreover high vowels exhibit quite extreme formant frequencies in MC.

Other interesting but non-significant dialect-dependent differences in vowel production may be found in Table 3. A trend for *F*2 for /a/ to be

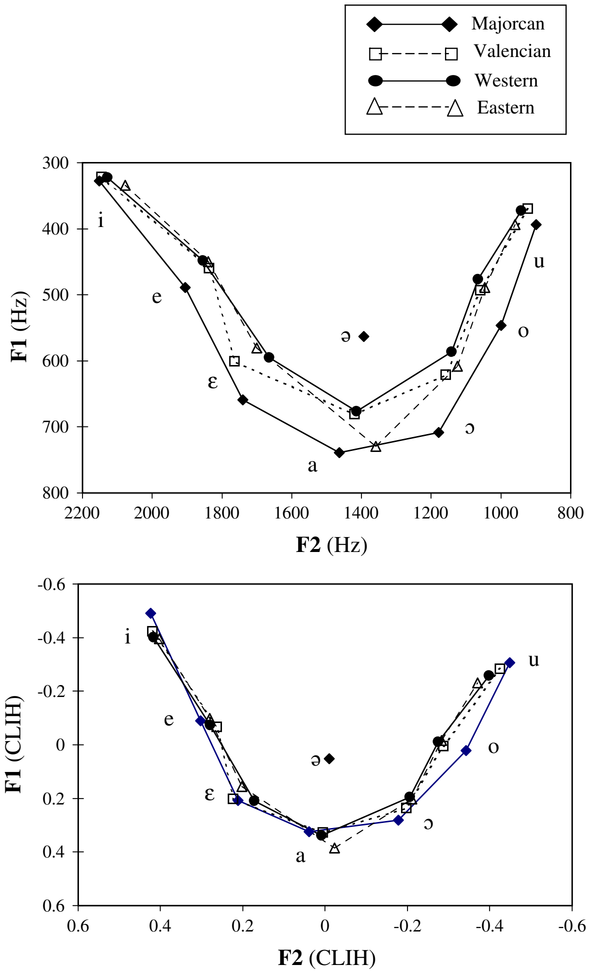

Fig. 2. Unnormalized (top) and normalized (bottom) $F1 \times F2$ values for the vowels of Majorcan, Valencian, Western Catalan and Eastern Catalan.

higher in MC than in the other three Catalan dialects suggests that the vowel in question is not only specially close but also most anterior in the Majorcan dialect; moreover, in addition to MC and VC, WC also shows a lower $F1$ than EC. Regarding mid vowels, VC parallels MC in showing a higher $F1$ for /ɔ/ with respect to EC as well as to WC. Two other trends recall the significant differences for /ɔ/ reported above, i.e., a higher $F1$ for /ε/ in MC, VC and WC than in EC, and a higher $F1$ for /o/ in MC and VC than in the other two dialects.

3.1.2. Dorsopalatal contact

The top graphs in Fig. 3 display Q_p values for all vowels and speakers in MC (left), VC (middle) and EC (right). Averages across speakers of each dialect are presented in the lower graph.

All graphs show that dorsopalatal contact decreases with vowel height for /i/ > /e/ > /ε/ > /a/, reaches its minimum for /ɔ/, and is higher for /u/ than for /o/. EPG configurations in Fig. 1 reveal analogous vowel-dependent differences in dorsopalatal contact to the ones just described. Less dorsopalatal contact for low and back rounded vowels than for front vowels results from predorsum lowering as the tongue postdorsum is positioned for the formation of a lower pharyngeal, upper pharyngeal or velar constriction.

According to the upper and lower graphs of Fig. 3, the vowels of MC may be produced with less palatal contact than their VC and EC cognates which is in accordance with some $F1$ differences reported in the preceding Section 3.1.1. There is one exception, i.e., one of the Eastern Catalan speakers (DP) who shows less, not more dorsopalatal contact for front vowels than most MC and VC speakers. Measures of palate height indicate that this dialect-dependent difference is not conditioned by palate shape. Thus, in spite of exhibiting less contact, speaker DP has less, not more palate height (14 mm) than the two other Eastern Catalan speakers DR (20.5 mm) and JC (17 mm). Moreover, contact degree is roughly the same for all MC speakers in spite of the fact that the palatal vault is higher for speaker AR than for speakers BM, MJ, ND and CA, i.e., 26 mm vs. 17–19 mm. VC speakers exhibit similar degrees of tongue contact and comparable palate heights, i.e., about 18–21 mm.

Correlation analyses between dorsopalatal contact and formant frequency data yielded high r values, i.e., −0.673 (Q_p-$F1$) and 0.802 (Q_p-$F2$). r values are negative for Q_p-$F1$ since $F1$ decreases as dorsopalatal contact size increases for high vs. low vowels, and positive for Q_p-$F2$ since $F2$ rises with an increase in dorsopalatal contact for front vs. back vowels. Therefore, there appears to be a good agreement between acoustic and articulatory data which confirms the validity of dialect-dependent differences in vowel formant frequency.

3.2. The status of schwa

(a) According to the $F1 \times F2$ plots in Fig. 2, MC /ə/ occupies a central position somewhere in the mid vowel region just above the low vowel /a/. $F3$ values for /ə/ in Tables 2 and 3 are higher than those for

Table 2
Unnormalized $F1$, $F2$ and $F3$ frequencies for the vowels of four Catalan dialects

		Majorcan				Valencian				Western				Eastern		
		$F1$	$F2$	$F3$		$F1$	$F2$	$F3$		$F1$	$F2$	$F3$		$F1$	$F2$	$F3$
i	AR	311	2005	2688	VB	324	2199	2678	MQ	331	2372	2934	DR	302	2093	2773
e		491	1786	2550		476	1937	2681		444	1989	2729		444	1868	2619
ɛ		675	1654	2479		684	1719	2679		618	1809	2539		645	1652	2382
a		715	1468	2477		699	1440	2631		676	1479	2501		755	1356	2251
ɔ		700	1247	2478		633	1139	2641		603	1140	2326		674	1145	2221
o		557	1096	2452		486	1014	2706		484	1084	2444		495	1036	2232
u		380	949	2415		391	924	2761		390	843	2614		375	919	2360
ə		546	1439	2571												
i	BM	346	2351	2918	JM	341	2155	2498	PR	297	2024	2659	DP	320	1913	2629
e		526	2092	2753		486	1831	2466		419	1794	2538		452	1755	2610
ɛ		724	1926	2648		641	1754	2432		544	1564	2321		591	1674	2392
a		814	1611	2569		675	1468	2415		641	1316	2305		741	1284	2431
ɔ		769	1217	2639		654	1267	2326		531	1044	2113		641	1085	2371
o		595	1043	2516		509	1169	2217		437	971	2159		509	1027	2318
u		413	936	2601		387	974	2346		341	924	2254		399	1027	2301
ə		585	1451	2593												
i	MJ	348	2211	2896	MS	291	2093	2619	AL	342	2052	2669	JC	328	2036	2468
e		487	1892	2795		438	1764	2566		483	1801	2533		469	1769	2631
ɛ		660	1711	2447		523	1772	2424		587	1639	2524		584	1703	2644
a		718	1396	2357		618	1349	2444		666	1472	2546		728	1404	2725
ɔ		686	1122	2326		582	1106	2329		609	1197	2399		564	1097	2575
o		522	982	2643		477	1023	2345		499	1165	2369		497	1045	2515
u		409	899	2807		350	955	2289		415	1055	2328		384	952	2597
ə		566	1361	2709												
i	ND	324	2094	2536	VG	328	2293	2830	AG	326	1938	2691	JO	369	2299	2861
e		461	1886	2595		439	1989	2754		440	1738	2364		444	1990	2566
ɛ		604	1710	2600		572	1954	2719		561	1574	2311		549	1779	2449
a		696	1341	2572		738	1519	2476		609	1366	2256		776	1392	2491
ɔ		636	1110	2574		651	1164	2632		543	1197	2136		589	1146	2480
o		497	936	2663		491	1011	2668		474	1067	2022		469	1041	2504
u		402	899	2579		369	876	2723		384	981	2030		408	943	2591
ə		531	1329	2611												
i	CA	310	2096	2622	AV	324	1988	2448	GR	317	2254	2745	PJ	353	2048	2578
e		480	1870	2585		459	1664	2406		455	1950	2596		440	1813	2431
ɛ		631	1696	2448		584	1621	2353		664	1740	2506		535	1694	2303
a		753	1502	2457		674	1321	2453		790	1441	2400		647	1356	2415
ɔ		752	1194	2606		588	1111	2296		646	1131	2229		575	1153	2263
o		561	940	2683		501	1076	2107		491	1040	2286		474	1086	2272
u		366	812	2784		352	887	2290		332	908	2357		404	957	2306
ə		589	1386	2588												
i		328	2151	2732		322	2145	2615		323	2128	2740		334	2078	2662
e		489	1905	2656		460	1837	2575		448	1854	2552		450	1839	2571
ɛ		659	1739	2524		601	1764	2521		595	1665	2440		581	1700	2434
a		739	1464	2486		681	1419	2484		676	1415	2402		730	1358	2462
ɔ		708	1178	2525		621	1158	2445		586	1142	2240		608	1125	2382
o		547	1000	2591		493	1059	2409		477	1065	2256		489	1047	2368
u		394	899	2637		370	923	2482		372	942	2317		394	960	2431
ə		563	1393	2614												

Data are given for five individual speakers of each dialect (above) and across speakers (below).

low and mid back rounded vowels and comparable to $F3$ for mid front vowels and /u/. Fig. 3 reveals that, analogously to /a/, this vowel is produced with a small degree of dorsopalatal contact.

Table 3
Normalized $F1$, $F2$ and $F3$ frequencies for the vowels of four Catalan dialects

		Majorcan				Valencian				Western				Eastern		
		$F1$	$F2$	$F3$		$F1$	$F2$	$F3$		$F1$	$F2$	$F3$		$F1$	$F2$	$F3$
i	AR	−0.529	0.347	0.067	VB	−0.451	0.442	−0.002	MQ	−0.395	0.496	0.130	DR	−0.510	0.416	0.146
e		−0.070	0.232	0.015		−0.068	0.316	0.000		−0.104	0.320	0.057		−0.125	0.302	0.088
ɛ		0.247	0.155	−0.014		0.295	0.196	−0.001		0.228	0.225	−0.015		0.248	0.180	−0.007
a		0.305	0.035	−0.014		0.316	0.019	−0.019		0.318	0.023	−0.030		0.406	−0.018	−0.063
ɔ		0.283	−0.127	−0.014		0.217	−0.216	−0.016		0.203	−0.237	−0.103		0.292	−0.187	−0.077
o		0.055	−0.256	−0.024		−0.046	−0.332	0.009		−0.017	−0.288	−0.053		−0.017	−0.287	−0.071
u		−0.327	−0.401	−0.040		−0.263	−0.425	0.029		−0.232	−0.539	0.014		−0.294	−0.407	−0.016
ə		0.036	0.015	0.023												
i	BM	−0.506	0.446	0.096	JM	−0.405	0.384	0.047	PR	−0.403	0.427	0.133	DP	−0.454	0.347	0.077
e		−0.088	0.330	0.038		−0.053	0.221	0.034		−0.059	0.307	0.086		−0.109	0.261	0.070
ɛ		0.232	0.247	−0.002		0.224	0.178	0.020		0.201	0.169	−0.003		0.160	0.213	−0.017
a		0.349	0.068	−0.032		0.276	0.000	0.013		0.366	−0.004	−0.010		0.386	−0.052	−0.001
ɔ		0.291	−0.212	−0.005		0.244	−0.147	−0.024		0.178	−0.235	−0.097		0.240	−0.220	−0.026
o		0.035	−0.367	−0.053		−0.006	−0.227	−0.073		−0.017	−0.307	−0.076		0.010	−0.275	−0.049
u		−0.331	−0.475	−0.020		−0.280	−0.410	−0.016		−0.266	−0.357	−0.032		−0.233	−0.275	−0.056
ə		0.018	−0.037	−0.023												
i	MJ	−0.429	0.468	0.102	MS	−0.447	0.416	0.076	AL	−0.385	0.351	0.074	JC	−0.407	0.391	−0.049
e		−0.092	0.313	0.067		−0.037	0.245	0.055		−0.041	0.220	0.022		−0.050	0.251	0.015
ɛ		0.211	0.212	−0.066		0.140	0.250	−0.002		0.155	0.126	0.018		0.170	0.212	0.020
a		0.295	0.008	−0.104		0.307	−0.023	0.007		0.281	0.019	0.027		0.391	0.019	0.050
ɔ		0.249	−0.210	−0.117		0.248	−0.221	−0.042		0.191	−0.188	−0.033		0.135	−0.227	−0.007
o		−0.023	−0.343	0.011		0.049	−0.300	−0.035		−0.009	−0.215	−0.045		0.009	−0.276	−0.030
u		−0.268	−0.431	0.071		−0.261	−0.368	−0.059		−0.192	−0.314	−0.063		−0.248	−0.369	0.002
ə		0.057	−0.017	0.035												
i	ND	−0.445	0.437	−0.021	VG	−0.410	0.453	0.053	AG	−0.358	0.347	0.179	JO	−0.304	0.469	0.111
e		−0.092	0.332	0.002		−0.117	0.311	0.026		−0.060	0.238	0.050		−0.120	0.324	0.002
ɛ		0.179	0.234	0.003		0.147	0.293	0.013		0.184	0.138	0.027		0.093	0.213	−0.045
a		0.321	−0.009	−0.007		0.401	0.041	−0.081		0.264	−0.003	0.003		0.439	−0.033	−0.027
ɔ		0.230	−0.198	−0.006		0.276	−0.224	−0.019		0.150	−0.135	−0.051		0.163	−0.227	−0.032
o		−0.015	−0.368	0.027		−0.005	−0.366	−0.006		0.015	−0.250	−0.106		−0.065	−0.323	−0.022
u		−0.228	−0.409	−0.005		−0.291	−0.508	0.014		−0.195	−0.334	−0.102		−0.205	−0.423	0.012
ə		0.050	−0.018	0.008												
i	CA	−0.541	0.423	0.010	AV	−0.397	0.399	0.048	GR	−0.458	0.460	0.118	PJ	−0.309	0.385	0.086
e		−0.103	0.309	−0.004		−0.049	0.221	0.031		−0.097	0.316	0.062		−0.088	0.263	0.028
ɛ		0.170	0.212	−0.058		0.191	0.195	0.008		0.281	0.202	0.027		0.107	0.195	−0.026
a		0.347	0.090	−0.054		0.334	−0.010	0.050		0.454	0.013	−0.016		0.298	−0.027	0.021
ɔ		0.346	−0.140	0.005		0.198	−0.183	−0.016		0.254	−0.229	−0.091		0.179	−0.190	−0.044
o		0.053	−0.379	0.033		0.039	−0.215	−0.102		−0.022	−0.313	−0.065		−0.013	−0.250	−0.040
u		−0.375	−0.525	0.070		−0.315	−0.408	−0.019		−0.412	−0.449	−0.035		−0.175	−0.376	−0.025
ə		0.101	0.009	−0.003												
i		−0.490	0.424	0.051		−0.422	0.419	0.044		−0.401	0.417	0.127		−0.396	0.403	0.074
e		−0.089	0.303	0.023		−0.066	0.263	0.029		−0.073	0.280	0.055		−0.099	0.281	0.041
ɛ		0.208	0.212	−0.027		0.202	0.223	0.008		0.210	0.172	0.011		0.156	0.202	−0.015
a		0.323	0.039	−0.042		0.327	0.006	−0.006		0.338	0.009	−0.005		0.384	−0.022	−0.004
ɔ		0.281	−0.178	−0.027		0.236	−0.198	−0.023		0.196	−0.205	−0.075		0.203	−0.211	−0.037
o		0.021	−0.342	−0.001		0.005	−0.288	−0.041		−0.011	−0.275	−0.069		−0.016	−0.283	−0.042
u		−0.306	−0.448	0.016		−0.282	−0.425	−0.010		−0.258	−0.398	−0.044		−0.232	−0.370	−0.017
ə		0.052	−0.010	0.008												

Data have been obtained applying the CLIH or Constant Logarithm Interval Hypothesis formula (see Section 2.2), and are given for five individual speakers of each dialect (above) and across speakers (below).

Unnormalized and normalized formant frequency values for the vowel in question occupy a very close position to those for the Majorcan vowel centroid and therefore, are roughly equidistant from

Table 4
Results for Bonferroni multiple comparisons tests on significant dialect-dependent vowel effects for the $F1$ data

	i	a	ɔ	u
Majorcan-Valencian				
Majorcan-Western	< **		> ***	
Majorcan-Eastern	< *	< **	> ***	< *
Valencian-Western			> *	
Valencian-Eastern		< *		
Western-Eastern				

Significant differences are given for each vowel and dialect pair with one, two or three asterisks depending on the level of significance. The sign of the significant effects is also given (<, 'smaller than'; >, 'greater than').
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

those for the peripheral vowels. Moreover, data across speakers and for the individual speakers indicate that MC stressed /ə/ has a slightly higher $F1$ and a lower $F2$ (563 Hz, 1393 Hz) than the centroid (552 Hz, 1477 Hz) and therefore, may be characterized as a low and retracted central vowel.

(b) A better characterization of /ə/ in Catalan may be achieved through inspection of data from Experiment 2 plotted in Fig. 4. The figure provides $F1 \times F2$ values for unstressed /ə/ in Eastern Catalan (empty triangles, top graph) and for unstressed and stressed /ə/ in Majorcan Catalan (empty and filled triangles, bottom graph) for all contexts and speakers.

Mean $F1 \times F2$ values for Eastern Catalan unstressed /ə/ across consonant contexts and speakers (big empty circle, upper graph) reveal that the vowel in question is located in the center of the vowel space. Its formant frequencies are analogous to those for a prototypical schwa both across speakers ($F1 = 471$ Hz, $F2 = 1479$ Hz) and for each of the individual speakers. Mean $F1 \times F2$ for Majorcan Catalan /ə/ in the lower graph show that this vowel also occupies the central space in the vowel triangle independently of whether it is stressed (big filled circle) or unstressed (big empty circle). Moreover, stressed /ə/ has a slightly higher $F1$ and lower $F2$ than unstressed /ə/, a difference which was also found to hold when data for the individual speakers were taken into consideration. This difference turned out to be statistically significant for $F1$ ($F(1,84) = 27.26$, $p < 0.001$) but not for $F2$. A comparison between the big empty circles in the upper and lower graphs also indicates that unstressed /ə/ has a lower $F1$ and $F2$ in Majorcan Catalan than in Eastern Catalan, and is therefore somewhat more close and more retracted in the former dialect vs. the latter.

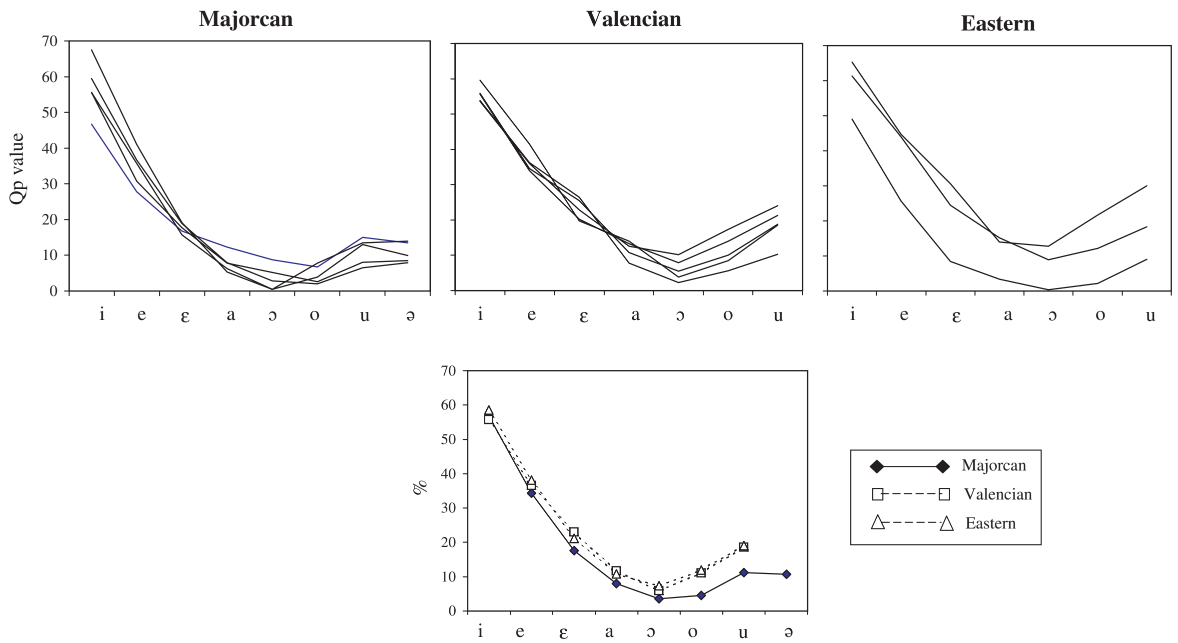

Fig. 3. (Top) Dorsopalatal contact (Q_p) values for speakers of Majorcan, Valencian and Eastern Catalan. (Bottom) Mean Q_p values across speakers of each Catalan dialect.

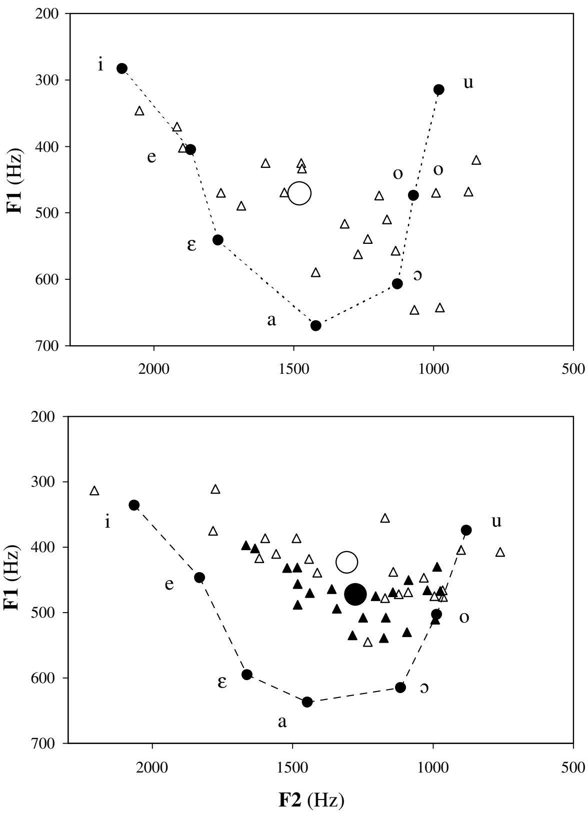

Fig. 4. (Top) $F1 \times F2$ values for unstressed /ə/ in seven consonant contexts according to three Eastern Catalan speakers (empty triangles), and corresponding means (big empty circle). (Bottom) $F1 \times F2$ values for unstressed and stressed /ə/ in seven consonant contexts according to three Majorcan Catalan speakers (empty and filled triangles, respectively), and corresponding means (big empty and filled circles). $F1 \times F2$ frequencies for /i, e, ε, a, ɔ, o, u/ according to the same Eastern Catalan and Majorcan speakers are also given in both graphs.

It may be concluded that /ə/ is a mid central vowel in EC and MC. Acoustic differences between unstressed and stressed /ə/ suggest that, in agreement with data from Experiment 1, the stressed cognate is produced with a somewhat lowered and retracted tongue body.

(c) Data in both graphs of Fig. 4 reveal the existence of much contextual variability for /ə/ whether stressed or unstressed such that $F2$ may be located at the front or back area of the vowel space, and $F1$ may vary along the high and mid vowel domains, depending on the articulatory characteristics of the contextual consonant. In addition to a main effect of stress condition for $F1$, ANOVAs on data for Majorcan stressed and unstressed /ə/ yielded an effect of consonant context for $F1$ and $F2$ ($F(6,84) = 7.73$, $p < 0.001$; $F(6,84) = 86.75$, $p < 0.001$), which appears to be associated with two consonant groups, namely, consonants causing $F1$ to decrease and $F2$ to increase (dentoalveolar, palatal, velar) and consonants exerting the opposite formant frequency changes (labial, /r/, /l/, labiovelar).

There are however some differences between the stressed and unstressed schwa varieties. According to the bottom graph, MC stressed /ə/ is somewhat less variable, more posterior (its $F2$ does not exceed 1700 Hz) and more open (its $F1$ always occurs above 400 Hz) than MC unstressed /ə/. In this respect, ANOVAs referred to above yielded a significant interaction between the stress and consonant factors for the $F2$ data ($F(6,84) = 5.07$, $p < 0.001$) but not for the $F1$ data. This interaction is related to the fact that consonants with a higher $F2$ locus cause unstressed /ə/ to exhibit a particularly high $F2$ frequency and thus, to be considerably front. Small formant frequency differences between the two stress-dependent allophones of schwa are comparable to those occurring between stressed and unstressed realizations of non-central vowels (Delattre, 1969).

Evidence presented so far reveals that Majorcan stressed schwa is a mid central vowel exhibiting much contextual variability. It could be considered a targetless vowel or else a vowel specified for a widely defined target at the mid central region of the vowel space.

3.3. *Vowel space dispersion and intervocalic acoustic distances*

(a) Table 5 reports dispersion measures for all four Catalan dialects and all individual speakers, i.e., mean Euclidean distances (left) and $F1$ and $F2$ ranges between point vowels (middle, right). Ranges correspond to the mean formant frequency values (middle) and to the maximal and minimal attested values (right).

The table shows dialect-dependent differences in the Euclidean distance measure varying in the progression Majorcan > Valencian > Western, Eastern. These differences turned out to be non-significant both for the unnormalized and normalized data according to one-way ANOVAs with dialect as the only independent variable. Two-way ANOVAs yielded a significant effect of context but not of dialect for the unnormalized data ($F(3,64) = 16.68$, $p < 0.001$), and a significant effect of dialect and context in the case of the normalized data

Table 5
Vowel space dispersion values and mean and maximal *F*1 and *F*2 ranges for unnormalized and normalized formant frequencies

		Vowel space dispersion		Mean formant ranges				Maximal formant ranges			
		Unnormalized	Normalized	Unnormalized		Normalized		Unnormalized		Normalized	
				*F*1	*F*2	*F*1	*F*2	*F*1	*F*2	*F*1	*F*2
	Majorcan	437.7	0.406	412	1253	0.813	0.873	660	1900	1.190	1.297
	Valencian	418.8	0.384	359	1222	0.749	0.843	540	1780	1.109	1.297
	Western	403.1	0.368	395	1186	0.781	0.771	720	1840	1.256	1.403
	Eastern	401.3	0.368	354	1118	0.737	0.815	600	1720	1.253	1.236
Majorcan	AR	360.4	0.374	404	1056	0.833	0.748	520	1440	1.099	1.117
	BM	511.4	0.440	468	1415	0.855	0.921	640	1800	1.190	1.233
	MJ	445.3	0.396	370	1312	0.724	0.900	500	1680	1.025	1.244
	ND	436.3	0.394	372	1284	0.766	0.846	500	1460	1.073	1.108
	CA	445.9	0.441	443	1196	0.888	0.948	560	1580	1.149	1.244
Valencian	VB	444.8	0.400	374	1275	0.767	0.867	500	1580	1.025	1.125
	JM	376.0	0.347	334	1181	0.682	0.795	420	1600	0.875	1.170
	MS	414.2	0.385	327	1138	0.754	0.785	440	1600	1.041	1.276
	VG	506.6	0.453	410	1416	0.811	0.962	500	1700	1.025	1.232
	AV	364.9	0.359	349	1101	0.731	0.807	460	1400	1.019	1.099
Western	MQ	485.6	0.408	453	1174	0.713	1.035	480	1820	1.229	1.090
	PR	394.4	0.378	421	886	0.769	0.785	420	1460	1.253	1.032
	AL	335.6	0.308	400	1084	0.666	0.665	440	1420	1.204	1.176
	AG	329.9	0.312	407	1356	0.623	0.681	440	1340	0.880	1.196
	GR	473.5	0.449	294	1091	0.913	0.909	700	1840	0.783	1.108
Eastern	DR	416.9	0.409	345	1529	0.916	0.823	580	1460	0.999	1.370
	DP	370.4	0.366	344	1101	0.840	0.622	600	1300	0.961	1.167
	JC	390.7	0.367	324	997	0.798	0.760	560	1480	0.865	1.071
	JO	470.0	0.389	282	957	0.743	0.891	480	1660	0.990	1.070
	PJ	377.0	0.328	473	1346	0.607	0.761	380	1420	1.253	1.403

Data are presented for four Catalan dialects and for the individual speakers of each dialect.

($F(3,64) = 3.06$, $p < 0.034$; $F(3,64) = 26.24$, $p < 0.001$). The dialect × context interaction turned out to be non-significant in both one-way and two-way ANOVAs. According to Tukey post-hoc tests, the weak effect of dialect for the normalized condition was associated with barely significantly higher dispersion values for MC than for WC ($p < 0.052$) and for MC than for EC ($p < 0.058$).

The absence of robust dialect-dependent differences in vowel space dispersion is consistent with vowel space dispersion values for the individual speakers in the table. Thus, dialects other than Majorcan include speakers exhibiting high mean Euclidean distances (VG in Valencian, MQ, GR in Western Catalan, JO in Eastern Catalan) while one Majorcan speaker (AR) has a relatively low dispersion value. In summary, there appears to be a trend for Majorcan to show a slightly higher degree of vowel space dispersion than the other three Catalan dialects though this trend is weak and barely significant.

Formant frequency ranges do not provide a clear picture either. In agreement with our initial hypothesis, MC exhibits larger mean formant frequency ranges than all other dialects, followed by WC in the case of *F*1 and by VC in the case of *F*2. This trend does not hold for maximal formant frequency ranges however. Data for individual speakers reveal again considerable variability independently of the dialect under analysis.

Correlation values between mean Euclidean distances and vowel durations across dialects were extremely low (0.30 and 0.22 for the normalized and unnormalized data set, respectively), meaning that the two parameters are independent of each other. A comparison between the duration and dispersion values indicate that vowels are generally longer in Majorcan than in the other three dialects but that this difference is not matched by sufficiently higher dispersion values. Moreover, vowels are somewhat more dispersed but not longer in VC than in WC and EC.

(b) In order to investigate the vowel equidistance hypothesis, Fig. 5 plots differences between the normalized formant frequency values for pairs of adjacent vowels excluding /ə/. Intervals are presented for $F1$ as a function of vowel height (top left graph), for $F2$ as a function of vowel fronting (top right graph), and for the corresponding Euclidean distance measures (bottom graphs).

According to the top left graph, $F1$ differences for all six vowel pairs turned out to be more similar in EC (i.e., neighbouring vowels approach equidistance in this dialect) than in MC, VC and WC (i.e., distances may be larger or smaller depending on the specific vowel pair taken into consideration). In particular, the three latter dialects show smaller $F1$ differences in the case of vowel pairs involving mid low and low vowels (i.e., /ɛ/-/a/ and /a/-/ɔ/) than in the case of pairs with high and mid high vowels (i.e., /i/-/e/, /e/-/ɛ/, /ɔ/-/o/ and /o/-/u/). It may also be seen that the $F1$ interval size for the pair /a/-/ɔ/ decreases in the progression EC > WC > VC > MC. To a large extent, these dialect-dependent differences in intervowel spacing appear to be positively related to dialect-dependent differences in $F1$ frequency for specific vowels, i.e., to lower mid low vowel realizations and higher low vowel realizations in MC, VC, WC than in EC.

The two groups of dialects were also found to differ regarding the relative $F1$ distances between vowel pairs. Thus, shorter distances for /ɛ/-/a/ and /a/-/ɔ/ in MC, VC and WC than in EC appear to be compensated by larger distances for the higher vowel pairs /i/-/e/, /e/-/ɛ/, /ɔ/-/o/ and /o/-/u/ in the three former dialects vs. the latter. Given that $F1$ frequency ranges between the point vowels /i/ and /a/ turned out to be quite similar across dialects (see step (a) above), it may be hypothesized that this compensatory mechanism is regulated by the need to keep the overall $F1$ frequency range constant.

As shown in the top right graph of Fig. 5, dialects exhibit similar $F2$ intervals for the pairs of vowels /i-u/, /e-o/ and /ɛ-ɔ/ along the fronting dimension. Euclidean distances in the two lower graphs are comparable to those for $F1$ and $F2$ in the upper graphs, except for those for /ɛ/-/a/ and /a/-/ɔ/ which happen to be smaller and more similar across dialects than the corresponding $F1$ distances.

These results provide support for dialect-dependent differences in the case of specific intervowel intervals, and for a trend towards compensation between intervowel distances at the low and high edges of the vowel space.

3.4. Variability

3.4.1. Dialect-dependent

In order to investigate possible dialect-dependent differences in vowel variability, Fig. 6 displays

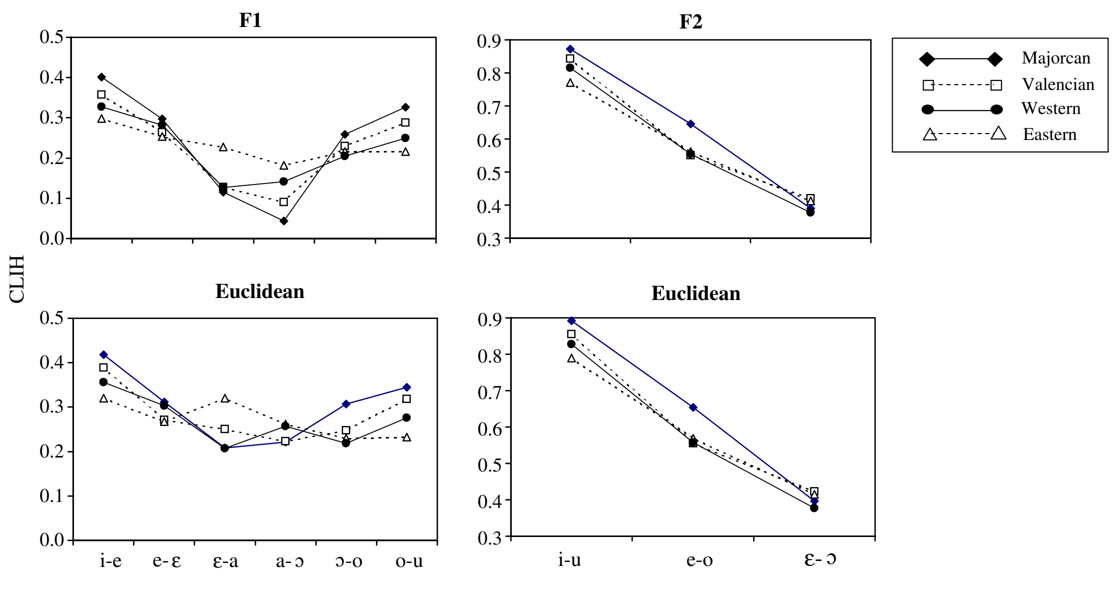

Fig. 5. (Top) Distances between normalized $F1$ and $F2$ values for adjacent vowels along the height and fronting dimensions. Results are presented separately for Majorcan, Valencian, Western Catalan and Eastern Catalan. (Bottom) Euclidean distances for the same vowel pairs.

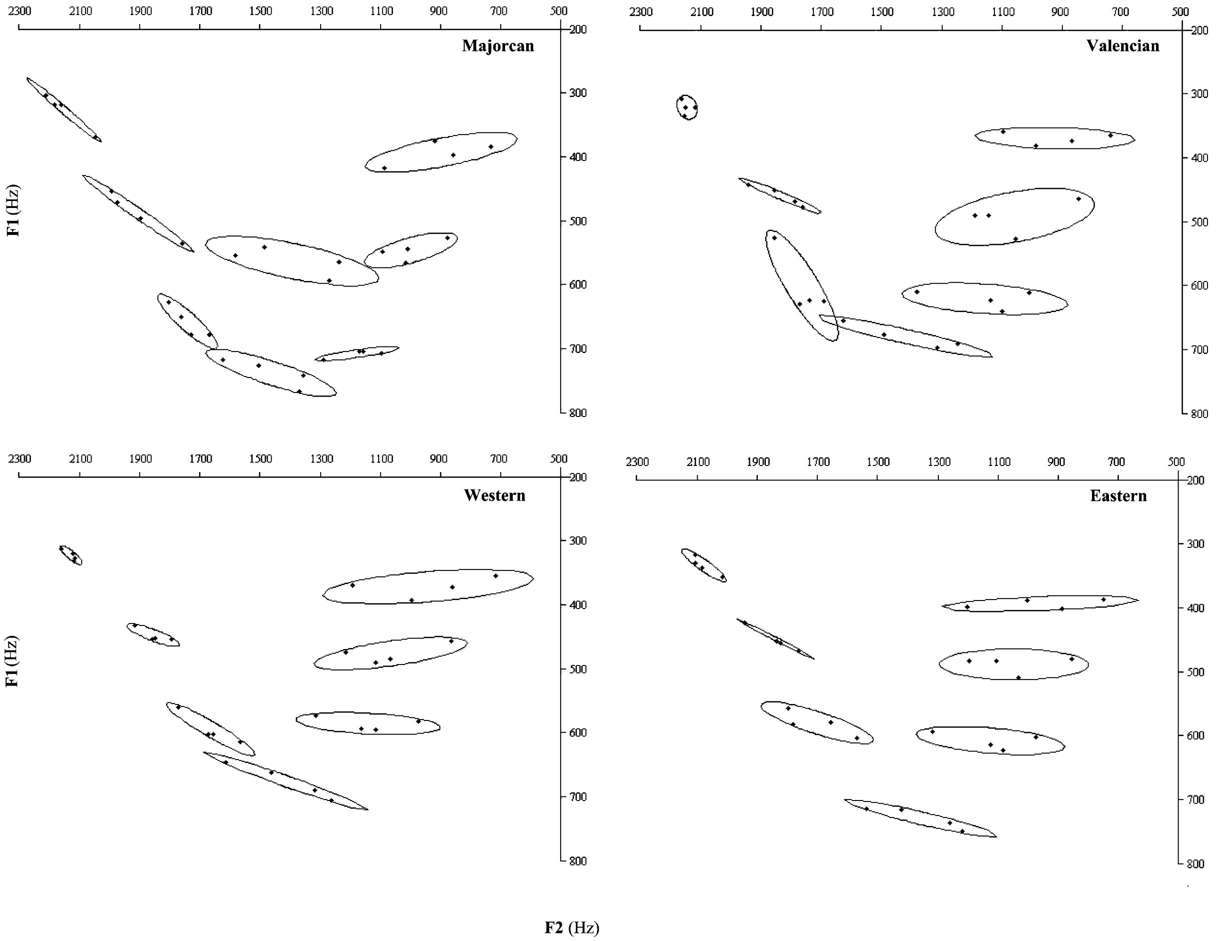

Fig. 6. $F1 \times F2$ values for vowels as a function of contextual labials, dentoalveolars, palatals and /l, r/ in four Catalan dialects. Ellipses with radii of two standard deviations have been drawn along axes oriented along the principal components of each vowel cluster.

ellipses containing mean $F1 \times F2$ values for the vowels of Majorcan, Valencian, Western Catalan and Eastern Catalan in the four contextual conditions (labial, dentoalveolar, palatal, /l, r/) across repetitions and speakers.

Variability patterns for the vowels of VC, WC and EC are consistent with trends in contextual variability described in Section 3.4.2 below. For all three dialects, front vowels (mostly /i/) are quite resistant to context-dependent effects while back vowels vary a good deal along the $F2$ dimension. Also as expected, MC stressed schwa is highly variable.

The most remarkable finding concerns the degree of variability for most peripheral mid vowels in Majorcan Catalan, i.e., mid low vowels (mostly /ɔ/) and /o/ are less variable in MC than in the other three dialects. The finding that only vowels lying close to the $F1 \times F2$ ellipse for stressed /ə/ exhibit restricted variability suggests that variability for those vowels may be conditioned by the presence of schwa, and could be in support of the notion that MC stressed /ə/ is specified for a mid central target. Inspection of vowel ellipses for the individual speakers of Majorcan Catalan also suggests the existence of a trend towards repulsion of peripheral vowels located near the mid central vowel region. Repulsion affects mostly formant frequency values for mid back rounded vowels in the context of dentoalveolar and palatal consonants. Less variability for /ɛ, ɔ, o/ in Majorcan than in Valencian, Western Catalan and Eastern Catalan could also be associated with special articulatory requirements on the production of mid or mid low vowels in the former dialect (see Section 4).

3.4.2. Context-dependent

Fig. 7 (upper graph) presents $F1$ and $F2$ standard deviations as a function of consonantal context for all Catalan vowels. According to the graph, contextual variability for $F2$ is clearly higher for back vs. front vowels; moreover, variability degree is lower for /i/ vs. /e, ɛ/ and higher for /u/ than for /a, ɔ, o/. These data are consistent with Recasens (1985) in that /i/ is most resistant and /u/ is most variable, though not so in showing more variability for mid back vowels than for mid front vowels. Also in agreement with previous studies, differences in $F1$ variability are directly related to vowel height for front and low vowels (/a, ɛ/ > /e/ > /i/) but not for back rounded vowels, and front vowels exhibit more $F1$ variability than their back rounded cognates as a general rule. MC stressed /ə/ exhibits a very high degree of contextual $F2$ and $F1$ variability.

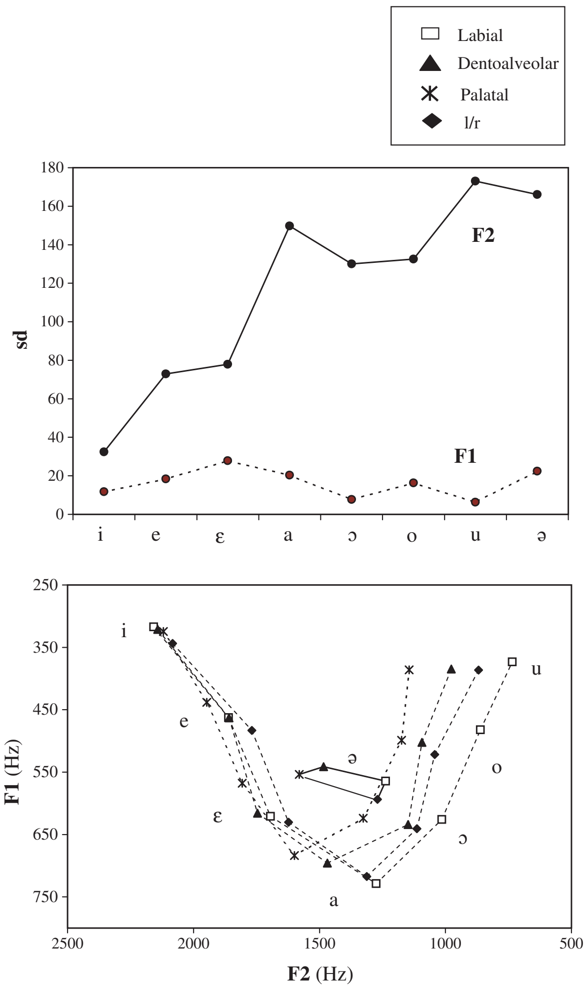

Fig. 7. (Top) Context-dependent $F1$ and $F2$ standard deviations for Catalan vowels. (Bottom) $F1 \times F2$ values for Catalan vowels as a function of contextual labials, dentoalveolars, palatals and /l, r/.

Information about the coarticulatory effects from consonants on vowels is provided in the bottom graph of the figure. This graph presents an $F1 \times F2$ plot of vowel realizations in the context of labials, dentoalveolars, palatals and /l, r/. According to the graph, mid front vowels and, to a large extent, /a/ undergo simultaneous consonant-dependent changes in $F1$ and $F2$ frequency, i.e., $F1$ decreases and $F2$ increases as we proceed from contextual /l, r/ and labials to contextual dentoalveolars and palatals. These patterns of C-to-V coarticulation may be accounted for by the consonant articulatory characteristics, i.e., tongue dorsum lowering and retraction and much jaw opening for /l, r/, tongue dorsum raising and fronting and little jaw opening for palatals and dentoalveolars, and lip closing for labials. C-to-V effects for back rounded vowels /ɔ, o, u/ affect $F2$ rather than $F1$, i.e., $F2$ for these vowels becomes higher in the neighbourhood of palatals and dentoalveolars and lower in the context of /l, r/ and labials. Consonantal effects for /ə/ resemble those for /a/ in that palatals and dentoalveolars cause this vowel to be more close and more anterior than labials and /l, r/.

3.4.3. Token-to-token and speaker-dependent

Fig. 8 shows data on token-to-token variability for the three vowels /i/, /a/ and /u/ as a function of consonant context and speaker. Each line within each graph corresponds to a specific contextual condition and contains one standard deviation for each speaker. Variability values are ordered from lowest to highest at the leftmost and rightmost edge of the horizontal axis, respectively.

A comparison between the height of the lines reveals the existence of analogous variability patterns to those reported in the literature (see Section 1): more $F1$ variability for /a/ than for /i, u/; differences in $F2$ variability decreasing in the progression /i/ > /u/ > /a/. The degree of token-to-token variability depends on the contextual environment to some extent. Thus, $F2$ for /i/ is often more variable in the context of /l, r/ (diamonds) than in other consonant contexts, while maximal $F2$ variability for /a/ and /u/ occurs in the neighbourhood of palatal consonants (crosses). This is the expected finding since a long spatial distance between the articulatory configurations for the consonant and the vowel

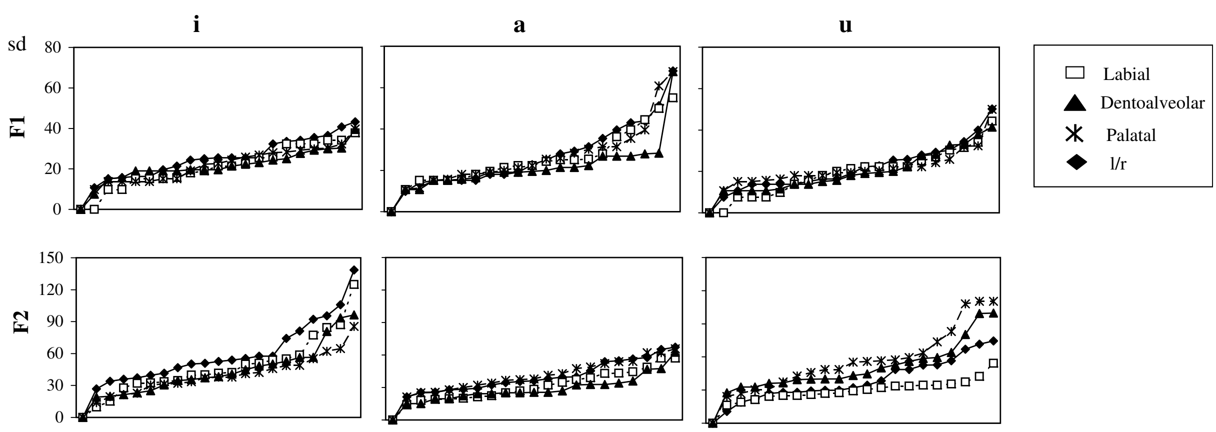

Fig. 8. Patterns of token-to-token variability for /i/, /a/ and /u/ ($F1$ and $F2$ data). Lines present standard deviations computed over vowel repetititions as a function of consonant context and speaker. Variability values are ordered from lowest to highest at the leftmost and rightmost edge of the horizontal axis, respectively. Outliers, i.e., $F2$ and $F3$ standard deviations above 150 Hz, have been excluded.

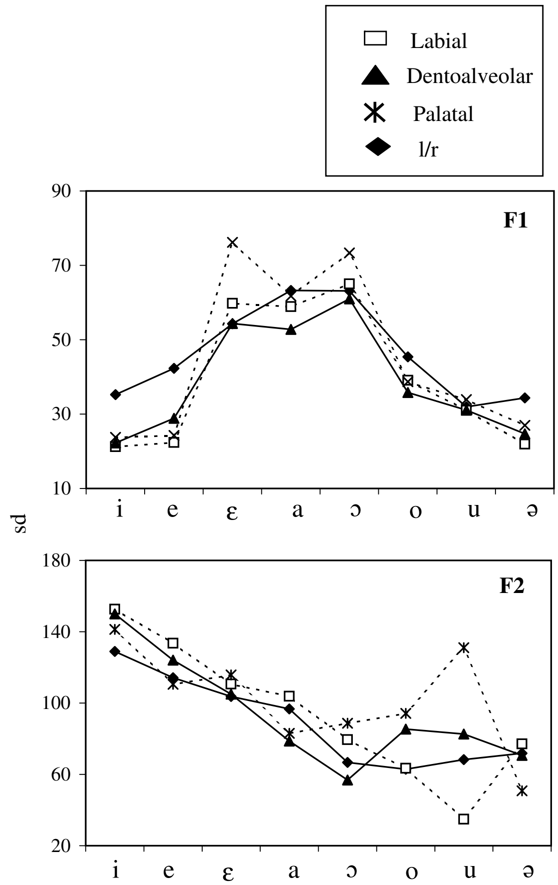

Fig. 9. Patterns of speaker-dependent variability for Catalan vowels ($F1$ and $F2$ data). Lines present standard deviations computed over all speakers' data in each consonant context condition.

in these segmental combinations may result in vowel undershoot.

Fig. 9 reports data on speaker-dependent variability for Catalan vowels. $F1$ and $F2$ values in the graphs correspond to standard deviations over all speakers' data in each consonant condition. Vowel variability patterns in the figure are similar to those reported in Fig. 8, i.e., more $F1$ variability for low vs. high vowels, and more $F2$ variability for front vs. back vowels. As a general rule, MC stressed /ə/ is specified for a low degree of $F1$ and $F2$ variability which suggests that speakers have little difficulty in achieving the articulatory configuration for this vowel.

4. Discussion

4.1. Vowel dispersion and vowel system size

A central goal of our investigation was to find out whether the vowel systems of four Catalan dialects exhibiting the same number of peripheral vowels occupy the same $F1 \times F2$ space or not. A related issue was to determine whether stressed schwa in Majorcan Catalan would count as an additional vowel and cause the vowel system to expand.

Results reported in this paper reveal that stressed schwa is realized as a mid central vowel occupying a somewhat lower and more retracted position than unstressed /ə/ and produced with little dorsopalatal contact but no pharyngeal constriction. Though not involving a back lingual constriction, it remains unclear whether stressed schwa should be specified for no target or for a mid central target. Indeed, as suggested by other languages in Section 1, the vowel in question is highly variable but acoustic variability is confined to $F2$ rather than to $F1$ and to the mid vowel region rather than to the high or low vowel regions. Moreover, the fact that it allows for little speaker-dependent and token-to-token variability suggests that speakers succeed quite easily in achieving an appropriate articulatory configuration for this vowel.

Assuming that schwa is not completely targetless, the Adaptive Dispersion Theory would predict that the eight vowel system of Majorcan Catalan should expand to a larger extent than the seven vowel systems of Valencian, Western Catalan and Eastern Catalan. Data reported in the Results section do not confirm a strong version of this hypothesis. As expected, Valencian, Western Catalan and Eastern Catalan turned out to exhibit similar degrees of vowel dispersion. In comparison to the other three Catalan dialects, Majorcan Catalan showed slightly higher but barely significant vowel space dispersion values. There was also a trend for formant frequency ranges between point vowels to be larger in Majorcan though not clearly so when maximally and minimally attested formant frequency values were taken into consideration. This finding appears to be in agreement with the observation that vowel expansion does not apply unless languages have a considerable number of vowels (Livjn, 2000).

It was hypothesized that, in addition to overall vowel dispersion, vowel system size could affect individual vowel variability. As expected, similar degrees of contextual variability for individual vowels were found to hold for the seven vowel systems of Valencian, Western Catalan and Eastern Catalan. However, mid vowel variability was less in Majorcan than in the other three dialects. This finding may be attributed to two different factors. One possible explanation is that, while playing a negligeable role in overall vowel space expansion, stressed schwa influences the degree of variability for neighbouring vowels by repelling their formant frequencies lying too close to the mid central region. Little variability for Majorcan mid or mid low vowels may also occur if those vowels are particularly tense and long. Long and tense English /i, æ, ɑ/ have also been reported to exhibit little context-dependent variability (Stevens and House, 1963).

An analysis of individual vowel variability for vowel systems with stressed /ə/ in other languages besides Catalan is needed in order to determine whether schwa behaves neutrally with respect to vowel system dispersion (Schwartz et al., 1997), and whether it may have a more local dispersion effect or not.

4.2. Intervocalic distances

Another research topic was intervocalic spacing the prediction being that all Catalan dialects ought to show similar formant frequency distances between adjacent peripheral vowels given that they all share the same number of non-central vowel phonemes.

This paper supports a version of the Adaptive Dispersion Theory which takes into account dialect-dependent differences in articulatory setting. A major finding was that dialects may differ regarding the formant frequency distances for specific vowel pairs. In particular, formant frequency intervals between mid low and low vowels turned out to be smallest for Majorcan and largest for Eastern Catalan, those for Valencian and Western Catalan falling in between. This dialect-dependent difference appears to be related to mid low and low vowel production, namely, to a lower realization of /ɔ/ and, less so, /ɛ/, and to a higher and somewhat more anterior realization of /a/, in those dialects exhibiting shorter intervocalic distances.

Data on vowel distribution along the height dimension suggest that $F1$ frequency distances between adjacent vowels tend to compensate with each other such that the maximal $F1$ range between the point vowels /i/ and /a/ is kept constant. Data for Majorcan, Valencian and Western Catalan reveal indeed that small distances between mid low and low vowels are compensated with large distances between high and mid high vowels and between mid high and mid low vowels. Eastern Catalan shows similar $F1$ distances between all pairs of adjacent vowels differing in height.

In combination with data on vowel dispersion reported in the previous section, this claim could be interpreted in support of a non-strict version of the Adaptive Dispersion Theory. Thus, while specific intervocalic distances may not necessarily be the same across dialects, dialects exhibiting the same vowel system size tend towards comparable degrees of overall vowel dispersion.

4.3. Variability patterns

Patterns of vowel variability appeared to be conditioned differently by contextual and non-contextual factors. Thus, while random and contextual $F1$ variation is less for close vs. open vowels, /i/ shows little contextual variation and much random $F2$ variability while /u/ exhibits the opposite behavior.

Contextual variability may be attributed to the articulatory requirements involved in vowel production. The finding that $F2$ variability increases with vowel opening and backing is in support of the hypothesis that, while tongue dorsum raising blocks lingual coarticulation, a relatively unconstrained tongue blade and predorsum for low vowels, back rounded vowels and schwa allows changes in tongue front height to occur. $F2$ variability also increases with lip unrounding for back rounded vowels. Differently from results reported in previous papers, $F2$ variability was less for mid front than for mid back vowels. $F1$ variability increases with vowel height (also for /ə/), and is less for mid back vs. mid front vowels perhaps since lip rounding prevents considerable variation in oral opening degree from taking place.

C-to-V effects are also conditioned by the relative compatibility between the articulatory gestures for adjacent vowels and consonants. In general, effects become most prominent when the target vowel is surrounded by consonants produced with antagonistic gestures. Thus, $F1$ frequency is generally higher in the context of consonants produced with a lower jaw (dark /l/, trill /r/) than in those showing more jaw raising (palatals). Lingual effects on low, back rounded vowels and schwa occur at the unconstrained tongue front next to palatal and dentoalveolar consonants, and involve a reduction in front cavity size and a raising of the $F2$ frequency. Effects on /i/ involve tongue dorsum lowering at the place of articulation and are mostly due to consonants produced with a low predorsum position and postdorsum retraction (dark /l/, trill /r/, /w/).

Regarding non-contextual variability, our data agree with those in the literature in showing more $F1$ variation for open vs. close vowels, and more $F2$ variation for front vs. low and back rounded vowels. These results suggest that random variability depends inversely on the precision involved in achieving the articulatory target for a given vowel in a specific segmental context. Thus, speakers appear to be more accurate in combining lip protrusion and a dorsovelar constriction for back rounded vowels (and in achieving an articulatory configuration for stressed /ə/) than in achieving the appropriate constriction location for /i/ or the appropriate degree of oral opening for /a/. This scenario is consistent with the finding by Perkell and colleagues that vowels ought to be most variable in tongue constriction fronting for /i/ and in tongue predorsum height for /a/.

Majorcan schwa resembles /u/ in being specified for a low degree of non-contextual variability but for much context-dependent variation. It thus appears that speakers do not have much difficulty in reaching the appropriate articulatory configuration for this vowel in a random task.

Acknowledgements

This research was funded by project BFF2003-09453-C02-01 of the Ministry of Science and Technology of Spain and FEDER, and by project 2001SGR425 of the Generalitat de Catalunya. I would like to thank two anonymous reviewers and Joaquín Romero for comments on previous manuscript versions.

References

Adank, P., 2003. Vowel Normalization. A Perceptual-Acoustic Study of Dutch Vowels. Ponsen & Looijen, Wageningen.

Bates, S.A., 1995.Acoustic characterisation of schwa: a comparative study. In: Elenius, K., Branderud, P. (Eds.), Proc. XIIIth Internat. Congress of Phonetic Sciences, Arne Strömbergs Grafiska, 3, Stockholm, pp. 230–233.

Bradlow, A., 1995. A comparative study of English and Spanish vowels. J. Acoust. Soc. Amer. 97, 1916–1924.

Bradlow, A.R., Torretta, G.M., Pisoni, D.B., 1996. Intelligibility of normal speech I: global and fined-grained acoustic–phonetic talker characteristics. Speech Comm. 20, 255–272.

Browman, C.P., Goldstein, L., 1992. "Targetless" schwa: an articulatory analysis. In: Kingston, J., Beckman, M.E. (Eds.), Papers in Laboratory Phonology II. Gesture, Segment, Prosody. Cambridge University Press, Cambridge, pp. 26–56.

Christov, P., 1987. Computer aided analysis of stressed and unstressed Bulgarian vowels from 30 male and 30 female speakers. In: Proc. XIth Internat. Congress of Phonetic Sciences, 3, Tallinn, Academy of Sciences of the Estonian S.S.R., pp. 121–124.

Delattre, P., 1969. An acoustic and articulatory study of vowel reduction in four languages. Int. Rev. Appl. Linguist. 7, 295–325.

Disner, S.F., 1983. Vowel quality: the relation between universal and language-specific factors. UCLA Working Papers in Phonetics 58.

Fant, G., 1960. Acoustic Theory of Speech Production. The Hague, Mouton.

Flemming, E.S., 2002. Auditory Representations in Phonology. Routledge, New York and London.

Gick, B., 1999. A gesture-based account of intrusive consonants in English. Phonology 16, 29–54.

Gick, B., Min Kang, A., Whalen, D.H., 2002. MRI evidence for commonality in the post-oral articulations of English vowels and liquids. J. Phonet. 30, 357–372.

Godínez, M., 1978. A Comparative Study of Some Romance Vowels. UCLA Working Papers in Phonetics, pp. 3–19.

Hardcastle, W.J., Jones, W., Knight, C., Trudgeon, A., Calder, G., 1989. New developments in electropalatography: a state-of-the-art report. Clin. Linguist. Phonet. 3, 1–38.

Herrick, D., 2003. An Acoustical Analysis of Phonological Vowel Reduction in Six Varieties of Catalan. Ph.D. Dissertation in Linguistics, University of California in Santa Cruz.

Hillenbrand, J., Getty, L.A., Clark, M.J., Wheeler, K., 1995. Acoustic characteristics of American English vowels. J. Acoust. Soc. Amer. 97, 3099–3112.

Hillenbrand, J., Clark, M.J., Nearey, T.M., 2001. Effects of consonant environment on vowel formant patterns. J. Acoust. Soc. Amer. 109, 748–763.

Hoole, P., Gfroerer, S., Tillmann, H., 1990. Electromagnetic articulatography as a tool in the study of lingual coarticulation, Forschungsberichte des Institut für Phonetik uns Sprachliche Kommunikation der Universität München, vol. 28, pp. 107–122.

Jongman, A., Fourakis, M., Sereno, J.A., 1989. The acoustic vowel space of modern Greek and German. Lang. Speech 32, 221–248.

Keating, P.A., Huffman, M.K., 1984. Vowel variation in Japanese. Phonetica 41, 191–207.

Keating, P., Lindblom, B., Lubker, J., Kreiman, J., 1994. Variability in jaw height for segments in English and Swedish VCVs. J. Phonet. 22, 407–422.

Kondo, Y. 1994. Phonetic underspecification in schwa. In: Proc. Internat. Congress of Spoken Language Processing 94, 1, Yokohama, The Acoustical Society of Japan, pp. 311–314.

Koopmans-van Beinum, F.J., 1973. Comparative phonetic vowel systems. J. Phonet. 1, 249–261.

Koopmans-van Beinum, F.J., 1994. What's a schwa. Phonetica 51, 68–79.

Liljencrants, J., Lindblom, B., 1972. Numerical simulation of vowel quality systems: the role of perceptual contrast. Language 48, 839–862.

Lindblom, B.J., 1986. Phonetic universals in vowel systems. In: Ohala, J.J., Jaeger, J.J. (Eds.), Experimental Phonology. Academic Press, London.

Livjn, P., 2000. Acoustic distribution of vowels in differently sized inventories—hot spots or adaptive dispersion. PERILUS, 23.

Magen, H., 1989. The extent of vowel-to-vowel coarticulation in English. J. Phonet. 25, 187–206.

Manuel, S., 1990. The role of contrast in limiting vowel-to-vowel coarticulation in different languages. J. Acoust. Soc. Amer. 88, 1286–1298.

McDougall, K., 2003. Vowel-to-vowel coarticulatory evidence of the 'targetful' nature of schwa. In: Palethorpe, S., Tabain, M. (Eds.), Proc. 6th Internat. Seminar on Speech Production. Macquarie University, Sydney, pp. 161–166.

Moon, S.-J., Lindblom, B., 1994. Interaction between duration, context, and speaking style in English stressed vowels. J. Acoust. Soc. Amer. 96, 40–55.

Munson, B., Solomon, N.P., 2004. The effect of phonological neighborhood density on vowel articulation. J. Speech Hearing Res. 47, 1048–1058.

Nearey, T., 1978. Phonetic Feature Systems for Vowels. Indiana University Linguistics Club, Bloomington.

Papçun, G. (1976). How may vowel systems differ? UCLA Working Papers in Phonetics 31, pp. 38–45.

Perkell, J.S., 1990. Testing theories of speech production; implications of some detailed analyses of variable articulatory data. In: Hardcastle, W.J., Marchal, A. (Eds.), Speech Production and Speech Modelling. Kluwer Publications, Dordrecht, pp. 263–288.

Perkell, J.S., Nelson, W.L., 1983. Variability in production of the vowels /i/ and /a/. J. Acoust. Soc. Amer. 77, 1889–1895.

Peterson, G.E., Barney, H.L., 1952. Control methods used in a study of the vowels. J. Acoust. Soc. Amer. 24, 175–184.

Pisoni, D.B., 1980. Variability of vowel formant frequencies and the quantal theory of speech. A first report. Phonetica 37, 285–305.

Pols, L.C.W., Tromp, H.R.C., Plomp, R., 1973. Frequency analysis of Dutch vowels from 50 male speakers. J. Acoust. Soc. Amer. 53, 1093–1101.

Recasens, D., 1985. Coarticulatory patterns and degrees of coarticulatory resistance in Catalan CV sequences. Lang. Speech 28 (2), 97–114.

Recasens, D., 1986. Temes de variació dialectal del català. In: Veny, J., Pujals, J.M. (Eds.), Actes del Setè Col.loqui Internacional de Llengua i Literatura Catalanes. Publicacions de l'Abadia de Montserrat, Barcelona, pp. 523–544.

Recasens, D., 1999. Lingual coarticulation. In: Hardcastle, W.J., Hewlett, N. (Eds.), Coarticulation. Cambridge, Cambridge University Press, pp. 80–104.

Recasens, D., Espinosa, A., 2005. Articulatory, positional and coarticulatory characteristics for clear /l/ and dark /ɫ/. Evidence from two Catalan dialects. J. Int. Phonet. Assoc. 35, 1–25.

Schwartz, J.-L., Boë, L.-J., Vallée, N., Abry, C., 1997. Major trends in vowel system inventories. J. Phonet. 25, 233–253.

Stevens, K.N., 1989. On the quantal theory of speech. J. Phonet. 17, 3–46.

Stevens, K.N., House, A., 1963. Perturbation of vowel articulations by consonantal context: An acoustical study. J. Speech Hearing Res. 6, 111–128.

Van Bergem, D.R., 1994. A model of coarticulatory effects on the schwa. Speech Comm. 14, 143–162.

Wood, S., Petterson, T., 1988. Vowel reduction in Bulgarian: The phonetic data and model experiments. Folia Linguist. 22, 239–262.