web-sls 00.02 15.04.00

WEB-SLS The European Student Journal of Language and Speech	ESCA EACL ELSNET

Acoustic Analysis of Singleton and Geminate Nasals in Italian

Marco Mattei and Maria Gabriella Di Benedetto

INFOCOM Department
University of Rome La Sapienza
Via Eudossiana 18
00184 Rome, Italy

marcoyyz@tin.it
gaby@acts.ing.uniroma1.it

Abstract

Acoustic correlates of singleton *vs*. geminate nasals in Italian were investigated on the basis of acoustic analyses carried out on Italian disyllabic words. In the analysed words, the singleton *vs*. geminate consonant appeared in the symmetrical context of the three Italian vowels [a, i, u]. Time related, frequency related and energy related parameters were examined. Time parameters were all based on durational measurements performed within the consonant and surrounding vowels. Frequency parameters, such as formants, fundamental frequency and energy based parameters were computed at different sampling points all through the analysed words. Results showed that the durations of the consonant and pre-consonant vowel were significantly different in singleton *vs*. geminate words. Moreover, the ratio between the above durations was significantly related to gemination. These results were in agreement with previous studies on the gemination of Italian stops and fricatives. However, contrarily to what observed for stops and fricatives, nasal geminate consonants also exhibited a significantly larger energy than their singleton counterparts.

[Note: the phonetic font used in this paper is Lucida Sans Unicode, regular 12pt - this should be installed for correct rendering of phonetic symbols. The body of the paper is set in Arial 12pt.]

Introduction

In Italian, several minimal pairs are formed by words which can be distinguished only by the presence or absence of gemination of one of the consonants in the words. The words of the pair have different lexical representation; the geminate consonant is represented by a double grapheme (for example *pane* (bread) *vs*. *panne* (creams)).

How gemination is reflected in the acoustic properties of the utterance, and which of these properties are relevant to its perception is still an open problem. The purpose of the Gemination Project (GEMMA) which started at the University of Rome La Sapienza in 1992 is to examine the gemination phenomenon in all Italian consonants which appear in single and geminate forms, both from a production and a perception point of view. The above set of consonants includes stops, liquids, fricatives, nasals and affricates. Results on stop consonants were reported in Rossetti (1993, 1994) and Esposito and Di Benedetto (1999). Liquids were analysed in Argiolas *et al*. (1995) while the analysis of fricatives was reported in Giovanardi (1998) and Giovanardi and Di Benedetto (1998). The major findings were coherent in all the above studies; they indicated that gemination is revealed by time related parameters such as lengthening of the consonant and shortening of the pre-consonant vowel in the geminate forms. The relevance of these correlates was confirmed by a perceptual analysis performed on stops. The above studies also revealed some peculiarities of each class of consonants such as the quantitative variation of the durational parameters in geminate *vs*. singleton.

Gemination in languages other than Italian has been examined in different studies (Shrotriya, 1995; Blumstein *et al*., 1998; Rochet and Rochet, 1995) as already reported in Giovanardi and Di Benedetto (1998) in the July 1998 issue of this same Journal. Very recently (August 1999) a symposium on gemination across languages was held at the *International Conference of Phonetic Sciences* in San Francisco. The papers of the symposium referred to three languages of Indonesia (Cohn *et al*., 1999), to an Austronesian language, Pattani Malay (Abramson, 1999), to a Dravidian language, Malayalam (Local and Simpson, 1999), to Cypriot Greek (Arvaniti, 1999), and to Berber (Louali and Maddieson, 1999). The significant number of gemination papers presented at the above symposium testifies to the large interest on the topic and for the intense activity of several research groups around the world. Many of the results presented in the above papers were in agreement with the results obtained on the Italian language; in particular it was found that, both for Indonesian languages and Cypriot Greek, duration is the main cue to a categorical distinction between singletons and geminates. The study on Pattani Malay (Abramson, 1999) focused on the analysis of fundamental frequency (F0) variations with gemination of word-initial consonants and indicated that F0 varied with gemination, although not for all consonantal classes. In particular, F0 in nasal consonants was not affected by gemination. The analysis of Malayalam (Local and Simpson, 1999) stands a little apart from the other studies since it contradicted the finding that duration is the most salient correlate of gemination. In particular, it appeared that for Malayalam both spectral and temporal properties were relevant. Finally, the analysis of Berber focused on the problem of categorising stop consonants as geminates even when no corresponding singleton occurs in the analysed language. Results on Berber indicated that calling these consonants as geminates is appropriate, and that these consonants are characterised by specific closure durations.

The present study analyses gemination in Italian nasals, based on the GEMMA database. The set of nasals which can be geminated in Italian, within words, are [m, n], which forms a subset of the Italian nasals [m, n, ɲ].

The present paper is organised as follows. The speech materials and measurements are described in Section 1. Acoustic analyses carried out on the above speech materials are reported in Section 2. In Section 3, the results of the acoustic analyses are discussed. Section 3 also includes the conclusions and the indications for future work.

---

1. Speech materials and measurements

The GEMMA data-base was created in 1992 at the University of Rome La Sapienza (rapporto SPELL). Its description will be briefly reported here for convenience to the reader.

The GEMMA data-base contains VCV singleton words and their geminate VCCV counterparts, all symmetrical with respect to the vowel. The words in the data-base included the entire set of consonants which appear in singleton and geminate forms in Italian according to Muljacic (1972) i.e. [f, v, s, p, t, k, b, d, g, m, n, l, r, ʧ, ʤ]. The vowels in the words of the database were selected as the three Italian cardinal vowels [a, i, u] which is a subset of the Italian vowel set [i, e, ɛ, a, o, ɔ, u]. The words were not included in a carrier phrase with the aim of avoiding the influence on parameters such as stress and intonation in a way which would be difficult to control. Six adult native speakers of standard Italian (three males and three females) with no known articulatory impairment uttered the speech materials described above. Each word was repeated three times. Note that it is common in other studies on gemination to consider meaningful words imbedded in sentences. Our procedure in building up GEMMA was motivated by the strong need of having data with well controlled parameters, as a starting point for future more realistic settings.

The speech materials considered in the present study belong to the above set of data with a restriction to nasals [m, m:, n, n:]. The analysed words were therefore 6 for each consonant (corresponding to the three vowels) and 6 for each speaker in three versions, leading to a total of 6 x 3 x 6 x 2 = 216 utterances (108 singleton and 108 geminate).

The speech materials were produced in a sound treated room, and recorded using a high quality equipment at the Speech Laboratory of the INFOCOM Department at the University of Rome La Sapienza. There were three recording sessions for each speaker, corresponding to the three repetitions of the words. The subjects read the words on cards (presented to them by an operator) which were shuffled before each recording session. The operator was a phonetically trained subject who also served as a controller on the quality of the produced speech sample. Therefore, if a mistake occurred, or if a word was judged to be unnatural, the speaker was asked to be repeat it.

The set of words analysed in the present study is reported in Table I.

TABLE I
The complete set of words analysed

	M		N	
A	*ama*	*amma*	*ana*	*anna*
I	*imi*	*immi*	*ini*	*inni*
U	*umu*	*ummu*	*unu*	*unnu*

The speech materials were then digitised using a software named UNICE by VECSYS (Vecsys,1989) which allows the use of appropriate over sampling factors in order to obtain a correct A/D conversion. The speech signals were filtered at 5 kHz, sampled at 10 kHz, and the samples were represented by 16 bits, before being stored on a PC computer memory.

UNICE is also a speech analysis program which generates spectral displays such as spectrograms, DFT (Discrete Fourier Transform) or the LPC (Linear Predictive Coding) spectra. In the analysis presented below, the DFT spectral analysis was computed, using a Hamming window of 256 samples corresponding to about 26 ms at a sampling rate of 10 kHz (the signal was pre-emphasised with $\alpha = 0.95$).

There is a set of performed measurements which are standard for the GEMMA project, and therefore were also performed on nasals. These are in the time and frequency domains summarised as follows (frequency domain measurements were computed at different sampling times, as shown on Fig.1.):

1. duration of the pre-consonant vowel, indicated as V1d. The vowel onset was identified by the appearance of a glottal pulse followed by other regular glottal pulses. In those cases in which a glottal excitation was visible before regular vowel voicing, the vowel onset was taken as the beginning of regular vowel voicing, and the initial glottal excitation was discarded. Vowel offset was identified, by examination of both the waveform and the spectrogram.

2. duration of the vowel following the consonant, indicated as V2d. The V2 onset was identified, by visual inspection of both the waveform and the spectrogram. The V2 offset was identified as the temporal sampling point where the glottal pulse disappeared .

3. duration of the consonant, indicated below as Cd.
4. duration of the whole utterance, indicated as Utd.

$$E_{totV1} = \sum_{i=t1}^{t2} |Xi|^2$$

5. total energy of V1. X_i is the sample i in the interval $[t_1, t_2]$, t_1 and t_2 are the temporal sampling points of vowel onset and vowel offset, respectively.

$$P_{mV1} = \frac{E_{totV1}}{t2 - t1}$$

6. average power of V1.
7. total energy of C, indicated below as E_{totC} and computed as for V1, with t_1 and t_2 that corresponding to V1 offset and V2 onset, respectively.
8. average power of C, indicated below as P_{mC} and computed as for the average power of V1.
9. instantaneous energy at V1 centre, indicated as E_{iV1}, computed in a window of 256 samples centred on V1.
10. instantaneous energy at V1-C transition, indicated as $E_{iV1\text{-}C}$: The window of 256 samples is centred on V1 offset.
11. instantaneous energy at C centre, indicated as E_{iC} and computed as E_{iV1}.
12. instantaneous energy at C offset, indicated as $E_{iCoff,}$ computed right before the first 256 samples of V2 onset.
13. F0, A0, F1, A1, F2, A2, F3, A3, at V1 centre (where F1,F2 and F3 are the formants and A1, A2 and A3 their amplitudes), at V1 offset, at the transition from V1 to C, at V2 onset and at V2 centre.
14. F0 and A0 at the onset, at the centre, and offset of voiced consonants.

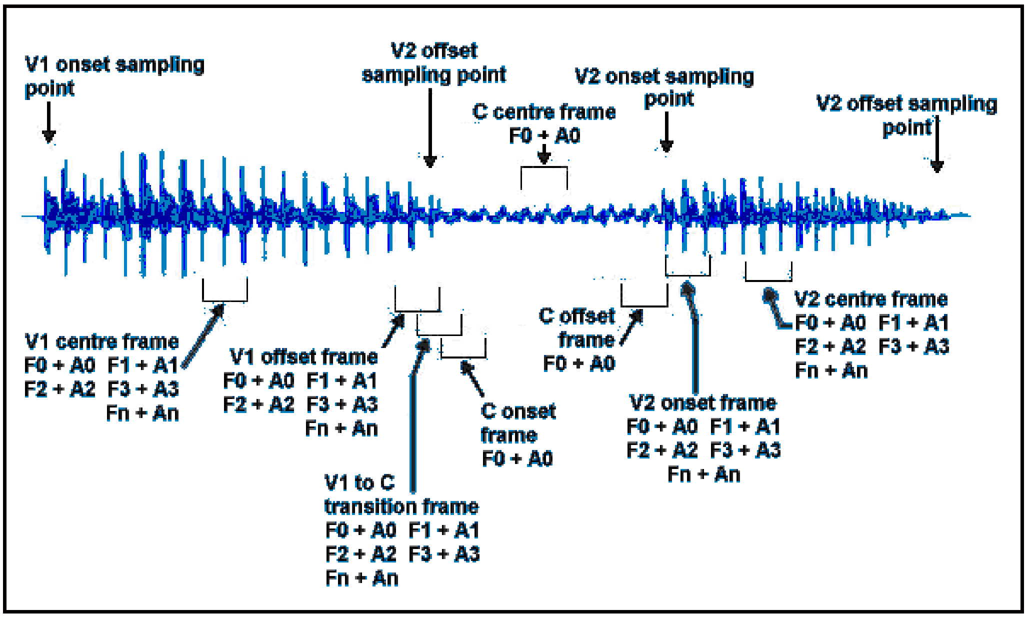

Fig.1 - Sampling points selected for the computation of the acoustic parameters and indication of the frames where frequency parameters were estimated.

A second set of measurements was specific to the present investigation on nasals. These measurements were :

1. the nasalisation formant Fn1 and its amplitude An, at the V1centre
2. the nasalisation formant Fn1 and its amplitude An, at the V1 offset
3. the nasalisation formant Fn1 and its amplitude An, at the transition from V1 to C
4. the nasalisation formant Fn1 and its amplitude An, at V2 onset
5. the nasalisation formant Fn1 and its amplitude An, at V2 centre

---

2. Results of the acoustic analysis

Results of the acoustic analysis is reported in the present paragraph. Statistical methods such as the Mono and Multivariate Anova, the maximum a-posteriori classification test, , the maximum likelihood classification test and the Spearman Rank Correlation Coefficient r_s were used in order to understand whether there was a significant difference among the geminate and singleton groups.

2.1 Results in the time domain

The values of the time-domain parameters were computed for each of the 108 singleton and 108 geminate utterances.

Table II contains the values for V1d, Cd, V2d, and Utd. In addition, the Cd/V1d ratio, averaged over all repetitions and speakers, for each consonant in the three vowel contexts [a, i, u] in geminate and singleton forms is reported. Table II also includes the standard deviation values obtained in correspondence to the above average values.

TABLE II
Average values (and standard deviations) of V1d, V2d, Utd and Cd/V1d, over all repetitions and speakers. All values in ms.

	V1d	(StD)	Cd	(StD)	V2d	(StD)	Utd	(StD)	Cd/V1d	(StD)
ama	**157.9**	*10.2*	**86.7**	*8.3*	**105.9**	*16.7*	**350.5**	*20.4*	**0.55**	*0.1*
amma	**117.8**	*15.4*	**210.1**	*27.9*	**106.3**	*21.1*	**434.1**	*41.2*	**1.82**	*0.4*
ana	**201.0**	*20.8*	**79.6**	*12.4*	**140.5**	*21.5*	**421.0**	*37.7*	**0.40**	*0.1*
anna	**133.8**	*16.6*	**201.5**	*23.5*	**126.8**	*30.4*	**462.0**	*53.3*	**1.54**	*0.3*
imi	**171.7**	*23.0*	**96.9**	*10.7*	**120.7**	*25.3*	**389.4**	*31.1*	**0.58**	*0.1*
immi	**118.2**	*22.7*	**227.1**	*32.0*	**120.2**	*23.6*	**465.5**	*40.6*	**2.01**	*0.6*
ini	**187.3**	*32.6*	**88.0**	*12.9*	**141.8**	*21.5*	**417.1**	*44.0*	**0.48**	*0.1*
inni	**117.8**	*21.8*	**229.1**	*37.6*	**132.3**	*24.4*	**479.2**	*30.9*	**2.08**	*0.9*
umu	**182.0**	*23.9*	**102.7**	*16.2*	**131.5**	*22.1*	**416.2**	*42.5*	**0.58**	*0.1*
ummu	**131.8**	*24.1*	**200.6**	*36.0*	**130.9**	*20.4*	**463.4**	*41.4*	**1.59**	*0.4*
unu	**201.2**	*23.1*	**89.9**	*12.0*	**139.9**	*25.7*	**431.0**	*39.4*	**0.45**	*0.1*
unnu	**128.0**	*19.5*	**202.1**	*32.0*	**129.1**	*25.0*	**459.2**	*40.7*	**1.62**	*0.4*

As can be noted from Table II, two parameters have quite different values in singleton *vs*. geminate words: V1d and Cd. V1 average duration was always higher in singletons than in geminates while the opposite effect was found for Cd. V2d and Utd did not vary as much in singleton *vs*. geminate.

The significance of the differences between the average values of V1d, Cd, V2d, and Utd, in singleton *vs*. geminate words was tested by the Anova test. Results are reported in Table III. They indicate that a strong significance is found for both for V1d and Cd (p<0.0001). As regards Utd, this parameter was found to significantly vary among singleton and geminate groups but not as much as V1d and Cd. The same effect is not highlighted for V2d.

In order to better understand the relation between V1d and Cd, a Spearman Rank correlation test was performed. Results indicate that a strong correlation between these two parameters is present if the singleton and geminate groups are merged into one set (Spearman correlation coefficient r_s= - 0.77). The same strong correlation is not observed if the singleton and geminate groups are kept separate (r_s not significant for singletons and r_s=-0.28 for geminates) Therefore, the correlation between V1d and Cd can be attributed to the presence of gemination. Moreover, the shortening of the geminate consonant provokes a lengthening of V1, and vice-versa.

TABLE III
Results of the Anova test performed on V1d, Cd, V2d and Utd. F-values are listed. The null hypothesis can be rejected at the p level of significance indicated on the Table. Green boxes indicate significantly different values

		A				I				U			
		V1d	*Cd*	*V2d*	*Utd*	*V1d*	*Cd*	*V2d*	*Utd*	*V1d*	*Cd*	*V2d*	*Utd*
m	***F ratio***	**84.98**	**324.43**	**0.00**	**59.67**	**49.34**	**268.26**	**0.00**	**39.92**	**39.40**	**111.01**	**0.01**	**11.40**
	p value	**0.00**	**0.00**	**0.95**	**0.00**	**0.00**	**0.00**	**0.95**	**0.00**	**0.00**	**0.00**	**0.93**	**0.00**
n	***F ratio***	**14.91**	**377.91**	**2.43**	**7.10**	**56.54**	**227.17**	**1.54**	**23.95**	**105.92**	**194.06**	**1.64**	**4.44**
	p value	**0.00**	**0.00**	**0.13**	**0.01**	**0.00**	**0.00**	**0.22**	**0.00**	**0.00**	**0.00**	**0.21**	**0.04**

The above result justifies the use of the Cd/V1d ratio in the attempt to classify geminate *vs*. singleton consonants. Table IV shows the results of the application of a one-dimensional Maximum Likelihood Criterion (Dillon W.R., Goldstein M., 1984) on the time-related parameters Cd, Cd/V1d and Utd. Note that the classification on both Cd and Cd/V1d leads to very good results (0.46% of error for both parameters, i.e. 1 error over 216 classifications) while unsatisfactory results are obtained with Utd .

Table IV - Results of the unidimensional Maximum Likelihood Criterion used for classifying singleton *vs.* geminate

	on Cd		on Cd/V1d		on Utd	
Context	***Errors***	***Err. %***	***Errors***	***Err. %***	***Errors***	***Err. %***
Overall	**1/216**	**0.46**	**1/216**	**0.46**	**57/216**	**26.38**
Male	**0/108**	**0.00**	**0/108**	**0.00**	**36/108**	**33.33**
Female	**1/108**	**0.92**	**2/108**	**1.85**	**21/108**	**19.44**
[a]	**0/72**	**0.00**	**0/72**	**0.00**	**19/72**	**26.39**
[i]	**0/72**	**0.00**	**1/72**	**1.39**	**12/72**	**16.67**
[u]	**1/72**	**1.39**	**1/72**	**1.39**	**20/72**	**27.78**
[m]	**0/108**	**0.00**	**1/108**	**0.92**	**25/108**	**23.16**
[n]	**0/108**	**0.00**	**1/108**	**0.92**	**34/108**	**31.48**

2.2 Results in the frequency domain

2.2.1 Frequency parameters

Table V reports the data on the frequency-based parameters (energy, formants, and F0) averaged over all utterances. Details on the above parameters can be found in (Mattei M.,1999). According to an Anova multivariate test, no significant effect of gemination was found on frequency parameters except for slight changes in the fundamental frequency (F0) and in the first formant (F1), when they are measured in very specific frames. F0 is about 12 Hz higher in the geminate form (+8%) in the frames at the border of V1 and C, i.e., V1offset, V1 to C transition and C onset frames.

F1 had significant variations only on the V2 onset frame: the geminate form is about 15 Hz higher than the single form (3%). Note however that the F1 variation might not be perceptually relevant since its value is very close to the least significant difference as indicated by Kewley-Port and Watson (1994).

TABLE V
Frequency-based parameters. Mean values and Standard Deviation with respect to all the repetitions, speakers, vowels and consonants. Frequencies are in Hz, amplitudes in dB.

V1 CENTER

	F0	*A0*	*F1*	*A1*	*F2*	*A2*	*F3*	*A3*
Singleton	**159.81**	**13.4**	**536.2**	**33.9**	**1535.9**	**32.2**	**2971.9**	**27.0**
(StD)	*46.4*	*7.1*	*287.8*	*8.4*	*803.9*	*9.4*	*460.9*	*9.5*
Geminate	**165.3**	**13.4**	**541.6**	**36.2**	**1553.7**	**32.9**	**3015.0**	**27.8**
(StD)	*44.5*	*7.5*	*292.6*	*6.9*	*784.5*	*8.4*	*457.3*	*8.5*

V1 OFFSET

	F0	*A0*	*F1*	*A1*	*F2*	*A2*	*F3*	*A3*
Singleton	**148.9**	**13.4**	**510.2**	**32.1**	**1574.3**	**28.4**	**2989.5**	**22.6**
(StD)	*44.6*	*6.0*	*253.4*	*7.7*	*775.2*	*9.2*	*458.3*	*7.5*
Geminate	**161.3**	**13.8**	**525.7**	**33.7**	**1572.1**	**30.4**	**2951.3**	**25.1**
(StD)	*43.6*	*7.0*	*278.2*	*6.3*	*769.9*	*8.0*	*466.0*	*8.3*

V1 TO C TRANSITION

	F0	*A0*	*F1*	*A1*	*F2*	*A2*	*F3*	*A3*
Singleton	**146.7**	**13.2**	**506.4**	**29.2**	**1570.3**	**24.9**	**2978.3**	**18.6**
(StD)	*43.7*	*5.7*	*262.2*	*7.4*	*778.0*	*8.1*	*449.4*	*6.8*
Geminate	**158.9**	**14.0**	**520.7**	**30.0**	**1558.7**	**26.5**	**2954.9**	**21.0**
(StD)	*43.0*	*6.3*	*278.0*	*6.4*	*770.2*	*7.6*	*484.5*	*7.1*

2.2.2 Energy-based parameters

Table VI reports the data on the energy-based parameters. The only energy parameter which appears to be significantly affected by the presence of gemination, on the basis of a multivariate Anova test, is the total energy of the consonant. The geminates have 4.4% increased energy. However, performing a Maximum Likelihood Criterion based on the consonant total energy parameter, leads to a poor 67% of correct classification. It should be finally noted that, since the most important parameter to influence gemination in the time domain was found to be Cd, one could reasonably expect that the geminate consonant would have increased energy.

2.2.3 Parameters related to nasality

In the present work, the study of the nasality parameters was restricted to a subset of utterances. In fact, it was possible to take a measure of the nasal formant Fn and its amplitude An only for the vowels [i,u] because the vowel [a] low frequency spectrum shape was found to be characterised by several local peaks which made it very uncertain to reliably detect the nasal formant.

Moreover, the nasalisation formant was more or less evident in the different utterances. V2 was nasalised (70% of the times for the V2 onset frame, and 66% for the V2 centre frame) more often than V1 (about 42% among the three V1 frames). In addition, it was found that V2 in the utterances including [n] was more often nasalised than in the utterances with [m] (about 25 % of the times). Finally, V2 in the geminates words was more often nasalised than the singletons (+10%).

Performing a multivariate Anova test on the nasality parameters, it was found that Fn was never affected by gemination. Oppositely, An was always significantly higher in geminates.

TABLE V *[continued]*

	C ONSET		**CENTRE**		**OFFSET**	
	F0	***A0***	***F0***	***A0***	***F0***	***A0***
Singleton	**143.2**	**13.8**	**139.7**	**13.3**	**136.6**	**12.5**
(StD)	*41.4*	*5.2*	*38.1*	*5.0*	*35.4*	*5.2*
Geminate	**155.4**	**14.7**	**142.2**	**13.8**	**137.4**	**12.8**
(StD)	*42.0*	*6.1*	*38.6*	*4.9*	*34.3*	*5.9*

	V2 ONSET							
	F0	***A0***	***F1***	***A1***	***F2***	***A2***	***F3***	***A3***
Singleton	**134.8**	**11.7**	**487.3**	**29.9**	**1610.1**	**26.7**	**2970.8**	**20.7**
(StD)	*33.3*	*5.4*	*261.8*	*7.8*	*787.2*	*8.4*	*445.9*	*7.3*
Geminate	**136.6**	**12.1**	**502.2**	**29.1**	**1600.9**	**27.6**	**3022.5**	**21.1**
(Std)	*33.7*	*5.4*	*265.2*	*7.0*	*767.9*	*6.8*	*454.1*	*6.5*

	V2 CENTRE							
	F0	***A0***	***F1***	***A1***	***F2***	***A2***	***F3***	***A3***
Singleton	**132.3**	**10.5**	**489.6**	**29.0**	**1586.4**	**25.2**	**2989.3**	**20.5**
(StD)	*29.9*	*5.5*	*269.9*	*7.7*	*792.2*	*8.5*	*450.6*	*7.7*
Geminate	**134.3**	**10.7**	**502.3**	**28.3**	**1592.0**	**25.5**	**3022.5**	**19.8**
(StD)	*32.0*	*5.5*	*278.4*	*7.2*	*792.3*	*6.9*	*493.1*	*7.4*

TABLE VI
<u>Energy based parameters</u>. Mean values and Standard Deviation with respect to all the repetitions, speakers, vowels and consonants. All values are in dB.

	Etot V1	**Pm V1**	**Etot C**	**Pm C**	**Ei V1 cent.**	**Ei V1-C**	**EiC cent.**	**Ei C offset**
Singleton	**96.0**	**63.4**	**88.5**	**58.9**	**88.0**	**84.5**	**82.8**	**83.1**
(StD)	*5.7*	*5.8*	*5.8*	*6.1*	*6.0*	*6.1*	*6.2*	*6.2*
Geminate	**95.2**	**64.4**	**92.4**	**59.2**	**89.2**	**85.0**	**82.9**	**83.2**
(StD)	*4.7*	*4.3*	*5.4*	*5.6*	*4.8*	*4.7*	*6.0*	*6.5*

3. Discussion

3.1 Effect of gemination

Time-related parameters showed strong evidence for a correlation with gemination. In particular, two parameters, V1 duration and C duration, were significantly different in singletons *vs*. geminates. The effect observed was of an elongation of the geminate consonant with respect of the singleton consonant, and a shortening of the vowel preceding the consonant in geminate *vs*. singleton words.

As regards the duration of the whole utterance, a significant difference was found among the two groups. However, the significance was not as high as for V1d and Cd, leading to the hypothesis that a compensatory effect is present, although it does not completely normalise the duration of the utterance.

Oppositely, the only frequency-related parameters which were significantly different in singletons *vs*. geminates were F0 and F1 when computed at very specific frames within the utterance (F0 at V1-C border, and F1 at V2 onset). While F0 variations (in the order of 12 Hz) might be also perceptually relevant, F1 variations (in the order of 15 Hz) are very close to the first formant frequency discrimination threshold (Kewley-Port and Watson, 1994). The other frequency parameters, i.e. formants and their amplitudes and F0 and F1 themselves sampled at other sampling points did not show any significant difference among singleton and geminate groups. The similar lack of statistical significance was found for the energy-based parameters with the exception of the total energy of the consonant which was higher for geminates. This last result can be related to the longer duration of the geminate consonant since, as noted, the total consonant power of the consonant was not found to differ among the two groups.

3.2 Comparison of acoustic correlates of gemination in nasals vs. fricatives and stops in Italian

For nasals it was found that the average difference between singles and geminates in terms of V1d is 59ms (-32% for geminates) and in Cd is 121 ms (+134% for geminates). This result is in agreement with previous findings on fricatives and stops. More specifically, for fricatives (Giovanardi M. ,1998) the average V1d difference was 49 ms (≈ -28% for geminates) and in Cd 98 ms (≈ +73% for geminates). As regards stops (Esposito A., Di Benedetto M.G, 1999), V1d difference was 43 ms (≈ -26% for geminates) and 92 ms for the stop closure duration (+101% for geminates). Therefore, the analysis on nasals confirms the previous studies and quantitatively the same effects found on fricatives and stops are emphasised.

The singleton/geminate classification based on the Maximum Likelihood Criterion using the Cd and Cd/V1d parameters leads to the following results:

1. 0.47% of errors in nasals for both parameters
2. 12 % of errors in fricatives for both parameters
3. 4% and 8% of errors in stops for Cd and Cd/V1d, respectively

In addition, it was found that the classifier set the Equal Probability Point (EPP) at the following values:

1. In nasals EPP=130 ms for Cd and EPP= 0.80 for Cd/V1d;
2. In fricatives EPP= 182 ms for Cd, and EPP= 1.30 for the Cd/V1d;
3. In stops EPP=128 ms for Cd (where here Cd is the closure duration), and EPP=0.93 for Cd/V1d.

The above result indicates that nasals and stops behave in a similar way in terms of Cd and Cd/V1d, but differently from fricatives. This difference, already pointed out by Bertinetto and Vivalda (1978) finds a first justification in the characteristics of nasals and stops being [-continuant] with respect to fricatives which are [+continuant].

In order to test the capability of classifying singletons *vs*. geminates, independently of the consonant, using Cd/V1d, it was found that based on an a-posteriori classification with a boundary set at Cd/V1d=1.02 only 8% of errors on stops (as with the MLC) and 8% of errors with fricatives (i.e. better than with the MLC) was found. For the nasals, the errors are 1.39% which is higher than 0.47% obtained with the MLC but still very satisfactory.

Finally, an additional similarity between nasals, fricatives, and stops was found; the Spearman Rank correlation coefficient between Cd and V1d was for all these consonants equal to values from –0.71 to -0.78.

3.3 Conclusions

As a general conclusion, the two most relevant outcomes of the present work can be summarised as follows.

First, the general tendency of shortening the pre-consonant vowel and of lengthening the consonant in a geminate utterance which was observed on stops and fricatives in previous studies, was confirmed for nasals. Secondly, the ratio of these two values appeared as a significant and valid way of synthesising the two effects in only one parameter.

The peculiarities of the nasal class was observed in terms of total energy of the consonant which was increased in the geminate case, and in a slight increase of F0 at V1 offset (which was also observed on the fricative class).

Finally, the nasal formant in V2 had larger amplitude in geminates than in singletons. This last finding can be interpreted in terms of an increase in the carry-over nasalisation effect, when the nasal consonant is in the geminate form.

References

1. Abramson A. S. (1999) "Fundamental frequency as a cue to word-initial consonant length: Pattani Malay*". ICPhS99* San Francisco, pp. 591-594
2. Argiolas F., Macrì F., Di Benedetto M.G. (1995) "Acoustic analysis of Italian [r] and [l]". *Journal of the Acoustical Society of America* 97, no. 5, pt.2, pp. 3418
3. Arvaniti A. (1999) "Effects of speaking rate on the timing of single and geminate sonorants*". ICPhS99* San Francisco, pp. 599-602
4. Bertinetto P.M., Vivalda E. (1978). "Recherches sur la perception des oppositions de quantite' en italien". *Journal of Italian Linguistics* 3, pp. 97-116.
5. Blumstein S.E., Pickett E., Burton M. (1998). "Effects of speaking rate on Singleton/Geminate consonant contrast in Italian". *unpublished manuscript*
6. Cohn A.C., Ham W.H., Podesva R. J.(1999) "The phonetic realisation of singleton-geminate contrasts in three languages of Indonesia". *ICPhS99,* San Francisco, pp. 587-590
7. Dillon W.R., Goldstein M. (1984) *Multivariate Analysis.* Wiley J. & Sons
8. Esposito A., Di Benedetto M.G (1999) "Acoustic and Perceptual Study of Gemination in Italian Stops". *Journal of the Acoustical Society of America*
9. Giovanardi M. (1998) *Analisi Acustica e Sintesi delle consonanti fricative singole e geminate in Italiano.* Degree Thesis in Electronics Engineering, Rome University La Sapienza
10. Giovanardi M. and Di Benedetto M.G. (1998)." Acoustic analysis of singleton and geminate fricatives in Italian". *European Student Journal of Language and Speech*
11. Kewley-Port D. and Watson C.S. (1994) "Formant-frequency discrimination for isolated English vowels". *Journal of the Acoustical Society of America*. Vol 95,No. 1, pp. 485-496

12. Local J. and Simpson A.P. (1999) "Phonetic implementation of geminates in Malayalam nouns" *ICPhS99* San Francisco, pp. 592-595

13. Louali N. and Maddieson I. (1999) "Phonological contrast and phonetic realisation: the case of Berber stops". *ICPhS99* San Francisco, pp. 603-606

14. Mattei M. (1999) *Analisi Acustica delle consonanti nasali singole e geminate in Italiano.* Degree Thesis in Electronics Engineering, Rome University La Sapienza

15. Muljacic Z. (1972) *Fonologia della lingua Italiana.* Il Mulino, Bologna

16. Rochet, L.B., and Rochet, A.P. (1995) "The perception of the single-geminate consonant contrast by native speakers of Italian and Anglophones*". ICPhS95*, edited by K. Elenius and P.Branderud, Vol. 3 (Arne Strombergs, Stockholm) pp. 616-619.

17. Rossetti R. (1994) "Gemination of Italian stops". *Journal of the Acoustical Society of America*, 95, 2pSP25, pp. 2874.

18. Rossetti R. (1993) *Caratteristiche acustiche del fenomeno di geminazione nelle consonanti occlusive italiane: applicazione all'adattamento automatico di pronunce straniere.* Degree Thesis in Electronics Engineering, Rome University La Sapienza

19. Shrotriya N., Siva Sarma A.S., Verma R., Agrawal S.S. (1995) "Acoustic and perceptual characteristics of geminate Hindi stop consonants. *ICPhS95*, edited by K. Elenius and P. Branderud, 4, (Arne Strombergs Grafiska Stockholm), pp.132-135

20. Vecsys (1989) *The Unice User Manual.* Vecsys - Chemin du Chene rond - 91570 Bièvres, France