INTERSPEECH 2016
September 8–12, 2016, San Francisco, USA

Effects of stress on fricatives: Evidence from Standard Modern Greek

Charalambos Themistocleous[1], *Angelandria Savva*[2], *Andrie Aristodemou*[2]

[1]University of Gothenburg
[2]University of Cyprus

charalambos.themistocleous@gu.se, aristodimou.andri@ucy.ac.cy, savva.angelandria@ucy.ac.cy

Abstract

This study investigates the effects of stress on the spectral properties of fricative noise in Standard Modern Greek (SMG). Twenty female speakers of SMG participated in the study. Fricatives were produced in stressed and unstressed positions in two vowel place positions: back and front vowels. Acoustic measurements were taken and the temporal and spectral properties of fricatives—using spectral moments—were calculated. Stressed fricatives are produced with increased duration, center of gravity, standard deviation, and normalized intensity. The machine learning and classification algorithm C5.0 has been employed to estimate the contribution of the temporal and spectral parameters for the classification of fricatives. Overall, duration and center of gravity contribute the most to the classification of stressed vs. unstressed fricatives.

Index Terms: fricatives, stress, spectral moments

1. Introduction

A fricative consonant is a noise caused by a turbulence of air in the pharyngeal or oral cavity. Fricatives' spectral shape is determined by the length of the cavity in the front of the constriction; see for a discussion [1, 2]. Previous studies on fricatives have shown that a number of factors may account for the spectral properties of frication noise, including the geometry configuration, voicing, and the segmental context e.g. [1, 3, 2].

To analyze the global and local properties of fricative noise, a line of research has employed the *spectral moments analysis*, which involves measurements at one or multiple windows of the speech signal. Overall, the spectral moments are statistical measures that show the shape of points in a probability density. The zeroth moment is the total probability and it is equal to one; the first moment is the mean, which stands for the *center of gravity*, namely the average energy concentration, the second is the variance, which is a numeric measure of the error, i.e. how much specific measurements deviate from the mean. The third moment is *skewness*, which reflects the shape of the distribution: a symmetric distribution has zero skewness, so in symmetric distributions the right and left tail are equal. When the right tail is longer than the left then the skewness is positive and when the left tail is longer than the right tail then the skewness is negative. In other words, the skewness stands for the *spectral tilt*, a positive skewness suggests a concentration of energy in the lower frequencies (i.e. a negative tilt) and a negative skewness denotes a high frequency concentration (i.e. a positive tilt) [3]. Finally, the fourth moment is *kurtosis*, which is a measure of the *tailedness* or *peakness* of the distribution and indicates how tall or flat is a distribution. A positive kurtosis indicates that the spectrum is characterized by clear peaks whereas a negative kurtosis suggests that the spectrum is more flat, without clearly defined peaks. Earlier studies have demonstrated that spectral moments successfully classify place of articulation, sibilant and non-sibilant fricatives and obstruent consonants from non-obstruent fricatives [4].

This study examines the effects of stress on the spectral properties of fricative consonants in Standard Modern Greek (SMG). Previous research on SMG fricatives focused on temporal properties of fricatives in a number of segmental contexts [5]. Current studies also provide evidence on the spectral, and amplitude parameters of SMG fricatives and on coarticulatory effects of fricatives on following vowels [6]. However, little research has been conducted on the effects of stress on fricatives' spectral shape.

By investigating typical speech, this study can potentially contribute to the overall research on atypical speech and on research that involves speakers with hearing loss, such as in cohlea traumas. Traumas can impair the perception of high frequency sounds, such as in fricatives. What is more, this study can have potential applications in text-to-speech and speech-to-text systems.

SMG is the official variety of Modern Greek. SMG phonetic inventory is comprised of voiceless and voiced fricative consonants articulated in the labio-dental ([f], [v]), the dental ([θ], [ð]), alveolar ([s], [z]), palatal ([ç], [ʝ]), and velar ([x], [ɣ]) places of articulation. Velar, and palatal fricatives are allophones, namely, palatal consonants occur before front vowels whereas velar consonants occur before back vowels; for Cypriot Greek see [7].

2. Methodology

For the purposes of this study, we have collected a large corpus of SMG fricatives from Athens, which is the capital city of Greece. 20 female speakers between 19 and 29 years participated in the study. Based on information from a demographic questionnaire, the participants constituted sociolinguistically homogeneous group: they originated from approximately the same socio-economic status and they were all university students. Namely, all SMG speakers were students at the University of Athens. All participants spoke English (as a second language); some SMG participants also knew French as a third language. None reported a speech or hearing disorder.

The speech material consisted of nonsense words, each containing one of the 10 SMG fricative consonants ([f v θ ð s z ç x ʝ ɣ]) in both stressed and unstressed word initial position before two vowel contexts /a i/. The nonsense words had the structure /C*V̀sa*/—where the C stands for Consonant and V for vowel /i/ or /a/—(e.g., /ˈfasa, ˈvasa, ˈθasa, etc./) and C*Vsà*/ (e.g., /faˈsa, vaˈsa, θaˈsa, etc./). The SMG experimen-

http://dx.doi.org/10.21437/Interspeech.2016-1057

Table 1: Experimental material: SMG keywords

Consonant	[f]	[v]	[θ]	[ð]	[s]
stressed	ˈfasa	ˈvasa	ˈθasa	ˈðasa	ˈsasa
unstressed	faˈsa	vaˈsa	θaˈsa	ðaˈsa	saˈsa
stressed	ˈfisa	ˈvisa	ˈθisa	ˈðisa	ˈsisa
unstressed	fiˈsa	viˈsa	θiˈsa	ðiˈsa	siˈsa
	[z]	[ç]	[x]	[ɟ]	[ɣ]
stressed	ˈzasa	–	ˈxasa	–	ˈɣasa
unstressed	zaˈsa	–	xaˈsa	–	ɣaˈsa
stressed	ˈzisa	ˈçisa	–	ˈɟisa	ˈɣisa
unstressed	ziˈsa	çiˈsa	–	ɟiˈsa	ɣiˈsa

tal material is shown in Table 1. The keywords were embedded in the carrier phrase: /ˈipes $< keyword >$ ˈpali/ (You told $< keyword >$ again).

The stimulus material consisted of 1480 stimuli. Each speaker produced two repetitions of the ten fricative categories in two stress conditions and in two vowel contexts as follows (20 speakers × 6 fricatives × 2 stress conditions × 2 repetitions × 2 vowels) and (20 speakers × 4 fricatives × 2 stress conditions × 2 repetitions × 1 vowel). Filler words were added in the carrier sentences to provide variation in the experimental material and to minimise speaker's attention on the experimental words.

The calculation of spectral moments took place in the DFT domain using procedures described in [8]. Linear mixed effects analysis was conducted using R [9] and lme4 [10]. Several models were built by adding variance components starting from the simplest model in a stepwise manner. The final model in 1 was selected by model comparison following the Akaikes Information Criterion (AIC) [11] and the Schwarzs Bayesian Information Criterion (BIC) [12].

$$DV \sim Segment * Stress * Vowel + (1|Speaker) \qquad (1)$$

where DV stands for the *Depended Variable*, namely duration, center of gravity, standard deviation, kurtosis, skewness, average intensity. *Segments* stands for the fricative consonants with ten levels (the ten SMG fricatives), *Stress* stands for the stress variable with two levels (stressed and unstressed), and *Vowel* stands for the following vowel with two levels (/a/ and /i/). The random effects were intercepts for speakers and items, as well as by-subject and by-item random slopes for the effect of segment.

To determine the classification rate of the temporal and spectral properties (e.g. duration, center of gravity, standard deviation, kurtosis, skewness, average intensity) of fricative noise, a classification tree model was fitted using Quinlan's C5.0 algorithm. For the model all the parameters in 1 were used as predictors for Stress. The analysis was conducted in R using C50 package.

3. Results

3.1. Duration

Overall, stressed fricatives are longer than unstressed fricatives (see Figure 1). The effects of Segment ($\chi^2(9) = 1307.90, p < .0001$), Stress ($\chi^2(1) = 498.75, p < .0001$), and Vowel ($\chi^2(1) = 67.38, p < .0001$) were highly significant. Also, the interactions of Segment × Stress ($\chi^2(9) = 23.09, p < .001$), Stress × Vowel ($\chi^2(1) = 29.21, p < .001$) and Segment × Stress × Vowel ($\chi^2(5) = 16.93, p < .001$)

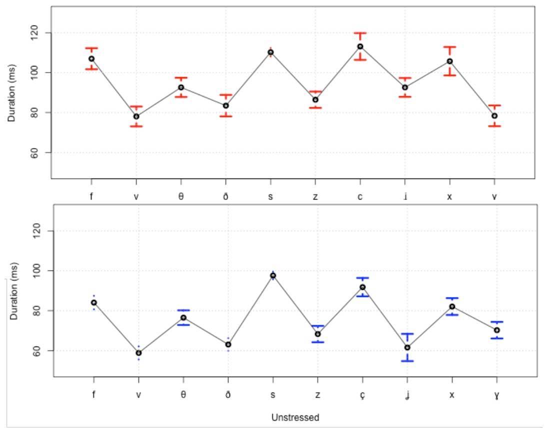

Figure 1: *Duration for stressed (top) and unstressed (bottom) fricatives in ms.*

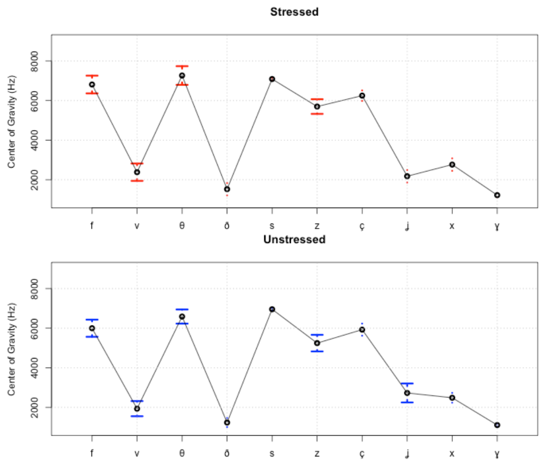

Figure 2: *Center of Gravity for stressed (top) and unstressed (bottom) fricatives in Hz.*

3.2. Spectral Characteristics

The first spectral moment, namely the center of gravity is higher in stressed fricatives than in unstressed fricatives. Also, voiceless fricatives have greater center of gravity than their voiced counterparts (in the same Place of Articulation) (see Figure 2). The effect of Segment ($\chi^2(9) = 7931.29, p < .0001$), Stress ($\chi^2(1) = 21.54, p < .0001$), and Vowel ($\chi^2(1) = 17.87, p < .0001$) were highly significant. The interactions of Segment × Stress ($\chi^2(9) = 37.36, p < .0001$), and Segment × Vowel ($\chi^2(5) = 28.96, p < .0001$) were significant.

Also, Stress had a significant effect on Standard Deviation (see Figure 3). More specifically, the effect of Segment ($\chi^2(9) = 3078.52, p < .0001$), Stress ($\chi^2(1) = 3.11, p = n.s.$), and Vowel ($\chi^2(1) = 10.77, p < .0001$) were highly significant. Also, the interactions of Segment × Stress ($\chi^2(9) = 43.89, p < .0001$), Segment × Vowel ($\chi^2(5) = 38.65, p < .0001$).

Significant effects of Stress are also observed in Skewness (see Figure 4) but only in the interaction Segment ×

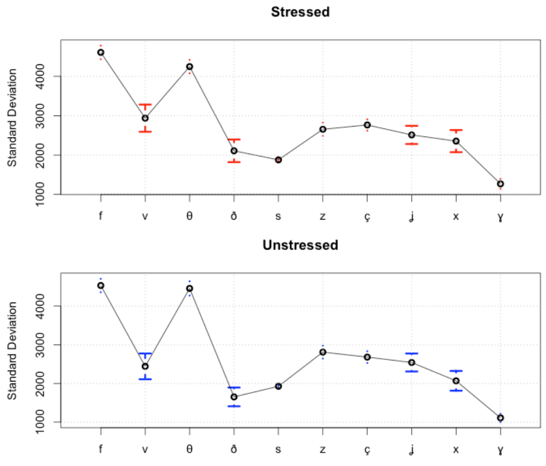

Figure 3: *Standard Deviation for stressed (top) and unstressed (bottom) fricatives.*

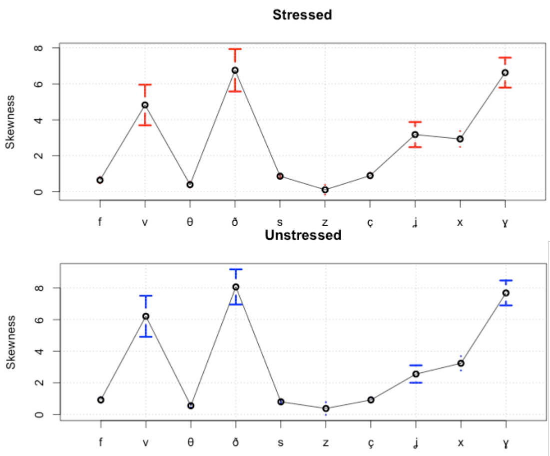

Figure 4: *Skewness for stressed (top) and unstressed (bottom) fricatives.*

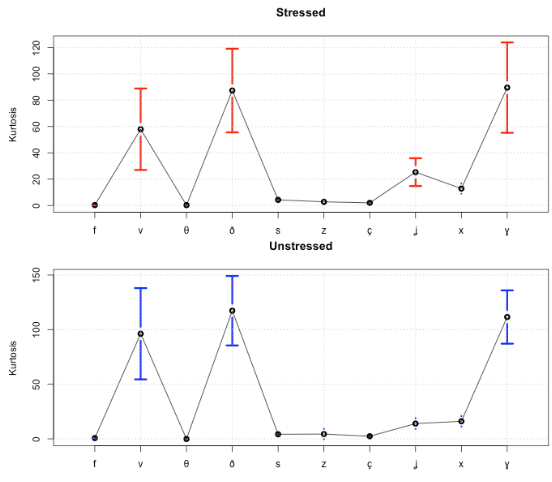

Figure 5: *Kurtosis for stressed (top) and unstressed (bottom) fricatives.*

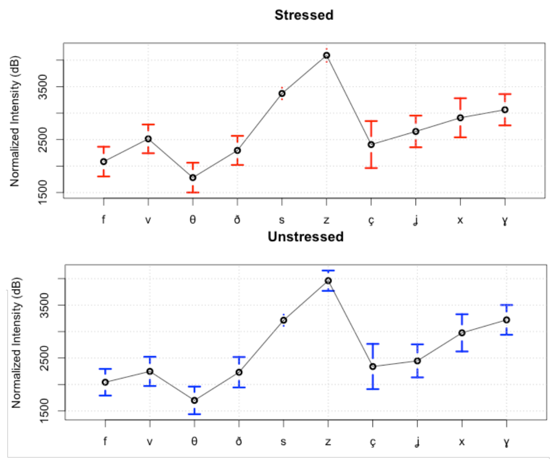

Figure 6: *Normalized intensity for stressed (top) and unstressed (bottom) fricatives in dB.*

Stress. More specifically, the effect of Segment ($\chi^2(9) = 2292.31, p < .0001$), Stress ($\chi^2(1) = 7.61, p < .001$), and Vowel ($\chi^2(1) = 12.89, p < .0001$) were highly significant. Also, the interactions of Segment $\times$ Stress ($\chi^2(9) = 32.88, p < .0001$), Segment $\times$ Vowel ($\chi^2(5) = 55.28, p < .0001$).

The fourth spectral moment is kurtosis (see Figure 5), which is influenced significantly by Segment ($\chi^2(9) = 583.73, p < .0001$), Stress ($\chi^2(1) = 5.15, p < .05$), and the following Vowel ($\chi^2(1) = 12.56, p < .0001$). The interactions of Segment $\times$ Stress ($\chi^2(9) = 24.41, p < .01$), Segment $\times$ Vowel ($\chi^2(5) = 62.84, p < .0001$).

3.3. Normalized Intensity

Overall, stressed fricatives have greater intensity than unstressed fricatives (see Figure 6). Only unstressed /x/ and /ɣ/ have greater intensity than the corresponding stressed sounds. Also, voiced consonants have higher intensity than their voicelss counterparts in place of articulation. The effects of Segment ($\chi^2(9) = 1138.06, p < .0001$), Stress ($\chi^2(1) = 11.25, p < .0001$), and Vowel ($\chi^2(1) = 4.52, p < .0001$) were highly significant. Also, the interaction Segment $\times$ Vowel ($\chi^2(1) = 11.60, p < .001$) was significant.

3.4. Classification Algorithm

The machine learning and classification algorithm C5.0 has been employed to classify the contribution of the temporal and spectral parameters examined for the classification of fricatives based on Stress. The results are shown in the decision tree in Figure 7. Overall, duration (100%), center of gravity (48.20%), normalized intensity (8.82%), and SD 2.24% better classify SMG stressed and unstressed fricatives.

4. Discussion

A number of well documented observations on the effects of place of articulation on the temporal and spectral properties of fricatives were observed in this study [3, 13, 14, 15]. Namely, the place of articulation had significant effects on all spectral properties of fricatives, including the temporal ones and can account for the intrinsic properties of fricatives: intrinsic duration,

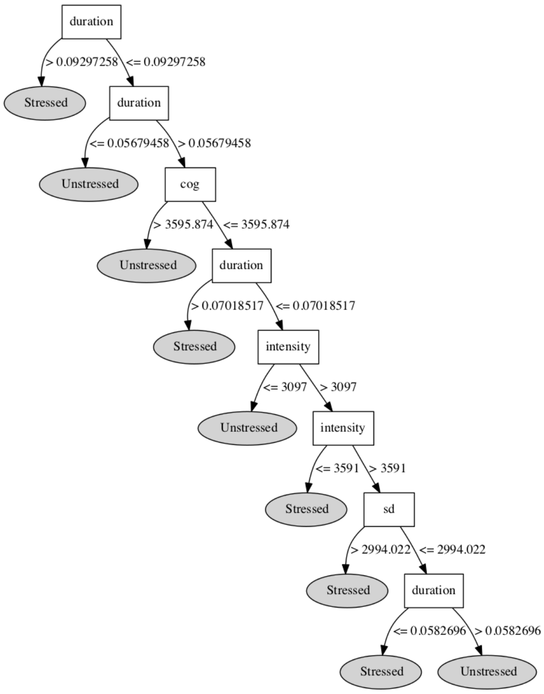

Figure 7: *Decision Tree produced by the machine learning and classification algorithm C5.0.*

intrinsic intensity etc.

Articulatory accounts for these effects were provided by the models of speech production; for a review see [1]. Another important effect are the effects of the following vowel on the spectral and temporal properties of SMG fricatives; see also [6]. The tongue displacement for the production of the following vowel: high front vowel /i/ vs. low central vowel /a/ changes the overall space in the front of the cavity and induces micro-articulatory effects on fricative production. Also, note a proportional account of syllable duration may account for the differences in the duration of fricatives preceding /a/ and fricatives preceding /i/: the first are shorter than the latter. In other terms, the fricative duration compensates for the shorter /i/ and longer /a/ vowel. Notably, these effects could be language or variety specific, see for a discussion [16].

The most obvious effects of stress on fricatives are related to an overall increase in the duration of fricatives: Stressed fricatives are significantly longer than unstressed fricatives. Stress lengthens the overall syllable duration (e.g. both consonants and vowels) [16]. Other effects of stress on fricative noise lead to increased values for center of gravity, kurtosis, and normalized intensity. The overall articulatory effort for the production of stress and hyperarticulation, i.e. an exaggeration of the linguistic cues for the production of stress can account for these effects. Earlier studies for the production of focus in American English reported similar results [15]. Overall, the classification model reported in this paper showed that that duration, center of gravity, normalized intensity, and standard deviation classify fricatives based on stress with high accuracy.

Overall, there has been little research on the effects of stress on the spectral properties of SMG fricatives as most studies on SMG stress investigate primarily $F0$, duration, and intensity; see [17]. One consequence of the emphasis on $F0$ is that earlier studies by design have excluded the study of voiceless sounds and fricatives. Therefore, by investigating the effects of stress on the temporal and spectral properties of Standard Modern Greek (SMG) fricatives, this study contributes to the overall research on the acoustic properties of stress in SMG.

Finally, these findings provide evidence for a distinct effect of stress on voiced and voiceless fricatives. Voiced fricatives are produced with longer duration and higher average intensity but with lower center of gravity. However, insofar as the present results do not specifically report the effects of voicing, this topic is open for further investigation.

5. References

[1] C. H. Shadle, "The aerodynamics of speech," in *The Handbook of Phonetic Sciences*, 2nd ed., W. J. Hardcastle, J. Laver, and F. E. Gibbon, Eds. Oxford: Blackwell Publishing, 2010, pp. 39–80.

[2] J. Harrington, "Acoustic phonetics," in *The Handbook of Phonetic Sciences*, 2nd ed., W. J. Hardcastle, J. Laver, and F. E. Gibbon, Eds. Oxford: Blackwell Publishing, 2010, pp. 81–129.

[3] A. Jongman, R. Wayland, and S. Wong, "Acoustic characteristics of English fricatives," *Journal of the Acoustical Society of America*, vol. 108, no. 3, pp. 1252–1263, 2000.

[4] K. Forrest, G. Weismer, P. Milenkovic, and R. N. Dougall, "Statistical analysis of word-initial voiceless obstruents: preliminary data." *Journal of the Acoustical Society of America*, vol. 84, no. 1, pp. 115–123, 1988.

[5] M. Fourakis, "A timing model for word-initial CV syllables in modern greek," *The Journal of the Acoustical Society of America*, vol. 79, no. 6, pp. 1982–1986, 1986.

[6] E. Nirgianaki, "Acoustic characteristics of Greek fricatives," *Journal of the Acoustical Society of America*, vol. 135, no. 5, pp. 2964–2976, 2014.

[7] A. Aristodemou, A. Savva, and C. Themistocleous, "The acoustics of Cypriot Greek fricatives," in *6th International Conference of Experimental Linguistics. ExLing 2015. 26-27 June 2015*, A. Botinis, Ed. University of Athens, 2015, Conference Proceedings, pp. 9–12.

[8] C. Shadle, "Acoustics and aerodynamics of fricatives," in *The Oxford Handbook of Laboratory Phonology*, A. C. Cohn, C. Fougeron, and M. K. Huffman, Eds. New York: Oxford University Press, 2012, pp. 511–526.

[9] R Core Team, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria, 2016.

[10] D. Bates, M. Mächler, B. Bolker, and S. Walker, "Fitting linear mixed-effects models using lme4," *Journal of Statistical Software*, vol. 67, no. 1, pp. 1–48, 2015.

[11] Y. Sakamoto, M. Ishiguro, and G. Kitagawa, *Akaike information criterion statistics*. Dordrecht: Reidel, 1986.

[12] G. Schwarz, "Estimating the dimension of a model," *Annals of Statistics*, vol. 6, pp. 461–464, 1978.

[13] G. W. Hughes and M. Halle, "Spectral properties of fricative consonants," *Journal of the Acoustical Society of America*, vol. 108, no. 3, pp. 1252–1263, 1956.

[14] M. Tabain, "Non-sibilant fricatives in English: Spectral information above 10 khz," *Phonetica*, vol. 55, no. 3, pp. 107–130, 1998.

[15] N. Silbert and K. de Jong, "Focus, prosodic context, and phonological feature specification: Patterns of variation in fricative production," *The Journal of the Acoustical Society of America*, vol. 123, no. 5, pp. 2769–2779, 2008.

[16] C. Themistocleous, "Edge-tone effects and prosodic domain effects on final lengthening," *Linguistic Variation*, vol. 14, no. 1, pp. 129–160, 2014.

[17] A. Arvaniti, "Greek phonetics: The state of the art," *Journal of Greek Lingusitics*, vol. 8, pp. 97–208, 2007.