A Corpus-based study on the Effects of Gender on Voiceless Fricatives in American English

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ABSTRACT

This paper investigates the acoustic characteristics of English fricatives in the TIMIT corpus, with a special focus on the role of gender in rendering fricatives in American English. The TIMIT database includes 630 talkers and 2342 different sentences, comprising over five hours of speech. Acoustic analyses are conducted in the domain of spectral and temporal properties by treating gender as an independent factor. The results of acoustic analyses revealed that the most acoustic properties of voiceless sibilants turned out to be different between male and female speakers, but those of voiceless non-sibilants did not show differences. A classification experiment using linear discriminant analysis (LDA) revealed that 85.73% of voiceless fricatives are correctly classified. The sibilants are 88.61% correctly classified, whereas the non-sibilants are only 57.91% correctly classified. The majority of the errors are from the misclassification of /θ/ as [f]. The average accuracy of gender classification is 77.67%. Most of the inaccuracy results are from the classification of female speakers in non-sibilants. The results are accounted for by resorting to biological differences as well as macro-social factors. The paper contributes to the understanding of the role of gender in a large-scale speech corpus.

1. Introduction

Fricatives are produced with a very narrow constriction in the oral cavity. A rapid flow of air through the constriction creates turbulence in the flow, and the random velocity fluctuations in the flow act as a source of sound (e.g. Stevens 1971; Jongman, Wayland *et al*. 2000; Wilde 2005). English fricatives are usually grouped into four classes according to their place of articulation: labiodental /f, v/, (inter)dental /θ, ð/, alveolar /s, z/, and palato-alveolar /ʃ, ʒ/. Most studies of fricatives exclude /h/, since it is considered the voiceless counterpart of the abutting vowel (e.g. Ladefoged, 1982).

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It is well established that among fricatives the acoustic characteristics of alveolar fricative /s/ differ in male and female speakers. Typically, energy in the alveolar fricative appears to be concentrated in the higher frequency domain in the female speech than in the male production. The acoustic difference is often accounted for by referring to the observation that female speakers are likely to have a shorter resonance cavity in front of the fricative constriction than males (Stevens 1998; Johnson 2012). That is, the biological determination of being male or female is a commonly assumed explanation for such a difference.

An alternative account for the acoustic difference of the alveolar fricative has been proposed in the sociophonetic research, which puts an emphasis on gender difference rather than biologically-termed sex difference (Smith 2007). According to Smith (2007), gender is interpreted as the sociocultural construct of being male and female. Strand (1999) noted that male/female vocal tract size differences are found largely behind the area of fricative construction. Because the different size of vocal tract is not in the front of the constriction site but in the

back, the fine phonetic variation of the alveolar fricative /s/ must be systematically related to macro-social factors such as gender rather than biological factors such as sex. In this regard, Eckert & McConnell-Ginet (2003: 62) manifest that "all the space within the territory of /s/ is free to be used for stylistic purposes, and all kinds of social meaning, including gender, are embedded in this stylistic variation."

Two immediate questions arise concerning the two competing explanations. The first question is why it is only /s/ that functions as an indexical feature of speech. Intuitively, the space within the territory of /ʃ/ is larger than that of /s/. The second question is whether it is really possible for sociophonetic factors not to be accompanied by physical adjustments. Apparently, it is possible in other grammatical domains, but it is very hard to be convinced that being different in gender is the only factor that brings about phonetic differences in /s/. As Strand (1999:88) points out, there is a possibility that males and females use different articulations for /s/. That is, there is an indication that more retracted variants of /s/ is employed by male speakers than female speakers in American English. If the point of constriction for male /s/ is more retracted than that of female /s/, it is natural that the frequency region for /s/ in females is higher than males. The macro-social factors are still carried out by fine biological and physical details.

There is a growing body of data from a number of languages which shows gender differences (*e.g.* Eckert and McConnell-Ginet 2003; Alam and Stuart-Smith 2011). Some of them may be purely socially motivated and others may have explanations in physical or phonetic domains. The first case concerns the durational differences between man and woman. With regard to duration, two main patterns are reported (1) that female vowels are longer than male and (2) that women produce greater differences between long and short vowel categories (Simpson and Ericsdotter 2003). It is not clear what the reason would be for the first case. But the second case of greater differences could be interpreted as an instances of hyperarticulation, which woman guard as the prestigious form. The second case is regarding vowel space. Vowel space is larger for women. Two explanations are entertained in the past research. Some experiments showed that a higher F0 makes it hard to distinguish vowels. This could be an explanation for a larger vowel space and more dispersed vowels for women. Some researchers, however, say that this is because women speak more clearly and articulate more. This is seen as the prestige or standard form, which women guard, in a Labovian perspective.

Little research exists which investigates the role of gender or sex in different members in the set of fricatives. For example, even though Stuart-Smith (2007) looked into the acoustic characteristics of alveolar fricative /s/ from the perspective of gender and social classes, other types of fricatives are left almost untouched. In this paper, the role of gender is reexamined in the acoustic realization of voiceless fricatives in American English. If the properties of fricatives are affected by gender rather than biological sex, it is possible that only alveolar fricative /s/ will be singled out as an indexical marker of speech for gender as claimed by Stuart-Smith (2007). If phonetic constraints, on the other hand, are more important than macro-social factors in realizing fricatives' acoustic features, the shape of the vocal tract will selectively affect the phonetic properties of voiceless fricatives. Argument in favor of the biological explanation on acoustic differences states that vocal tract differences could matter in the case of labiodental and interdental fricatives. Thus, we could expect that sibilants would have energy in higher frequency bands in female speech than in male speech, but non-sibilants would show similar distribution of fricative energies.

2. Methods

2.1 Corpus

The TIMIT database is used for the current study. TIMIT was designed jointly by the Massachusetts Institute of Technology, Texas Instruments, and SRI International under sponsorship for the development and evaluation of automatic speech recognition systems as well as the acquisition of acoustic phonetic knowledge (Byrd 1994).

Because of the quantity of speech and the segmentation and labeling, TIMIT provides a unusual corpus for phonetic research. The TIMIT database includes 630 talkers and 2342 different sentences, comprising over five hours of speech. The sentences are of three types: SA-type, SX-type, and SI-type sentences. The SA-type sentences are two calibration sentences that are spoken by every talker. These sentences were designed to 'incorporate phonemes in contexts where significant dialectal differences are anticipated' (Zue *et al.* 1988).

(1) Two calibration sentences in TIMIT
a. She had your dark suit in greasy wash water all year.
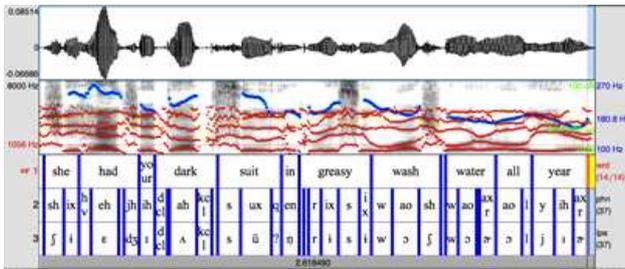b. Don't ask me to carry an oily rag like that.

Figure 1. An example of a calibration sentence 'She had your dark suit in greasy wash water all year.' (DR1/F_CJF0_SA1)

Additionally, 450 phonetically-compact sentences, *a.k.a* the SX sentences, were designed to incorporate a complete coverage of phonetic pairs. That is, *phonetically-compact* denotes that examples of phonemes in all possible left and right contexts are included. Finally, 1890 sentences were chosen to provide a variety of contexts and multiple occurrences of the same phonetic sequence in different word sequences. The *phonetically-diverse* sentences were called the SI sentence types. Each talker reads two calibration sentences, five from the phonetically compact sentences, and three from the phonetically-diverse group.

For the gender-based acoustic analyses of the voiceless fricatives, all the unvoiced fricatives /s/, /sh/ (or /ʃ/), /f/ and /th/ (or /ɵ/) were extracted from the TIMIT corpus. Table 1 presents the distribution of the voiceless fricatives organized by gender and following vowels[2].

The uneven distribution of phonemes and gender are thought to be limitations and shortcoming of TIMIT. The speech is read. The speakers are mostly white, mostly in their 20's and 30's, and, as noted above, mostly male (192 female vs. 493 male speakers).

2.2 Acoustic Feature Extraction

Fricatives are signalled by a large number of cues. Place of articulation can be distinguished by four spectral moments (mean, variance, skewness, and kurtosis of the frequency spectrum) (Forrest *et al.* 1988; Jongman *et al.* 2000), and by spectral changes in the onset of the subsequent vowel, particularly in the F2 (Jongman *et al.* 2000). Duration and amplitude of the fricatives are known to be related to place of articulation, primarily distinguishing sibilants from non-sibilants (Behrens &

2) /h/ will not be considered in the present study, because it is commonly regarded as a voiceless counterpart of an adjacent vowel (e.g. Ladefoged 1982). For convenience, /ʃ/ and /ɵ/ will be interchangeably marked by [sh] and [th], respectively.

Table 1. Distribution of fricative phones by post-fricative vowels and gender

	/f/		/s/		/ʃ/		/ɵ/	
	f	m	f	m	f	m	f	m
aa	19	39	12	30	8	22	0	1
ae	10	30	12	35	5	8	4	11
ao	50	128	32	67	4	29	4	11
aw	6	24	2	5	4	6	6	7
ax	26	41	44	144	10	21	9	19
ax-h	3	10	9	54	1	5	0	6
axr	54	123	14	40	3	11	4	15
ay	19	59	38	81	2	6	1	1
eh	16	47	81	163	12	24	2	14
er	34	58	30	62	9	32	7	28
ey	16	35	18	47	6	11	1	5
ih	43	115	56	134	17	63	34	80
ix	31	80	142	386	95	200	12	41
iy	26	59	152	310	150	336	16	39
ow	6	15	32	62	6	21	0	1
oy	0	2	4	11	0	0	0	0
uh	4	22	1	8	10	19	0	1
uw	3	9	10	35	5	3	0	0
u	2	15	133	331	9	22	1	5

Blumstein 1988; Baum & Blumstein 1987; Crystal & House 1988; Jongman *et al*. 2000).

On the basis of the findings in the previous studies, the present study extracts from the speech samples in the TIMIT corpus the following acoustic features concerning to place of articulation in English fricatives: (1) the spectral moments of mean and standard deviation (or dispersion), (2) overall noise amplitude, (3) fricative noise duration, (4) F2 onset. F2 onset values are examined by fixing the post-fricative vowels to be high front vowels ('ih' and 'iy' in Table 1), as the vowel quality may affect greatly the F2 values. A custom-made Praat script is used for the feature extraction, and R and its packages (*e.g.* pastecs, ggplot2, lda) are used for statistic analyses and visualization.

3. Results

Two types of statistical tests were conducted. The first type of statistical analyses is two-way ANOVAs for the acoustic features extracted. The two independent factors are places of articulation and gender. The second type is classification experiments using linear discriminant analysis (LDA) of the voiceless fricatives on

places of articulation and gender, respectively.

3.1. Statistical Analysis

Each of the two-way ANOVA tests on each acoustic features revealed main effects of fricative types (F(3, 5679), p<.001) and gender (F(1, 5679), p<.001). There was also an interaction between fricative types and gender (F(2, 5678), p<.001). To save the space, I will report below post hoc tests (i.e., Tukey HSD) that do not show differences.

3.1.1. Spectral moments

Spectral measurements can be useful for determining the articulatory positions of different fricatives (Gordon and Barthmaier 2002). For the fricative spectra, center of gravity and dispersion (or standard deviation) are two of the most commonly used acoustic features. Thus, these two spectral cues are presented below. Skewness and Kurtosis, which show more or less similar pattern to the first two spectral moments, will be used in the second part of the experiments of classification of places of articulation and gender classification.

Center of Gravity: The center of gravity corresponds to the frequency that divides the spectrum into two halves such that the amount of energy in the higher frequency regions is equal to that in the lower frequency region. Thus, a fricative with a lot of high-frequency energy will have a larger values of center of gravity (Forrest *et al.* 1998). Post-hoc analyses using Tukey HSD indicate that there is no difference of /f/ between male and female speakers (p>.98), between male /Ɵ/ and female /f/ (p>.93), between /f/ and /Ɵ/ of male speakers (p>.99).
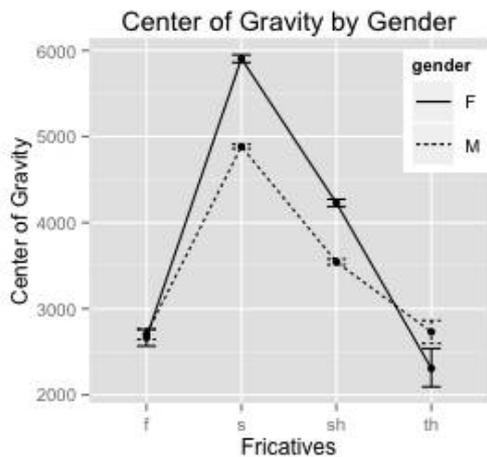

Figure 2 Center of Gravity

Dispersion: Dispersion provides a measure of whether energy is concentrated in a small band around the center of gravity or spread out over a wide range of frequencies. In Praat, this measure is referred to as 'standard deviation.' Post-hoc analyses using Tukey HSD indicate that no differences are found between /Ɵ/ and /f/ of females (p>.99), in /f/ between male and female (p>.99), between male /f/ and female /Ɵ/ (p>.99), and in /Ɵ/ between male and female speakers (p>.14).
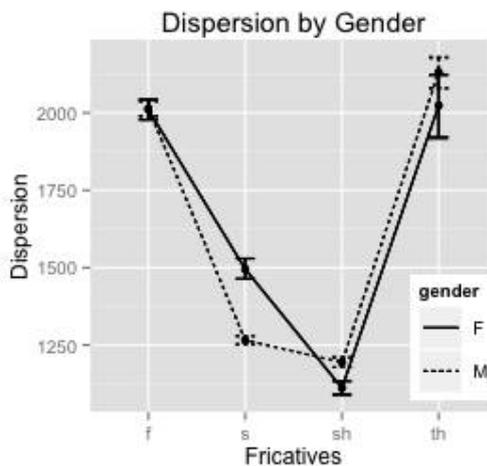

Figure 3. Dispersion

3.1.2. Amplitude

Most research concerned with fricative amplitude has focused on voiceless fricatives and converged on similar findings: sibilant /s, ʃ/ have a substantially greater amplitude than non-sibilant /f, Ɵ/. Within each group, however, the two fricatives are not different from each other (Jongman *et al.* 2000: 1254). The same pattern has been found for the TIMIT data, in that sibilant fricatives have higher amplitude than non-sibilant fricatives, and non-sibilant fricatives can not be distinguished further[3]. As for the sibilant fricatives, females clearly distinguish two sibilants with amplitude, but males do not. Post-hoc analyses using Tukey HSD indicate that there is no difference between /Ɵ/ and /f/ of females (p>.81), between male /f/ and female /Ɵ/ (p>.99), between /Ɵ/ and /f/ of males (p>.99) and between /ʃ/ and /s/ of males (p>.78).

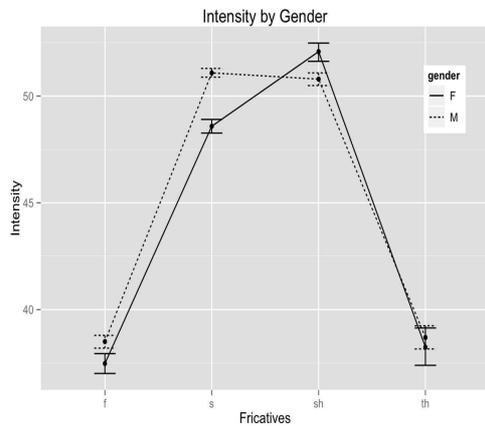3) Note that no normalization method has been applied to the amplitude.

Figure 4 Frication Amplitude

3.1.3. Noise Duration

Jongman *et al*. (2000: 1255) notes that "[n]oise duration serves to distinguish sibilant from non-sibilant fricatives, with /s, ʃ/ being longer than /f, θ/. Behrens and Blumstein (1988) found no difference in duration between /s/ and /ʃ/ and only a trend for /θ/ to be shorter than /f/.

The results of the present study agree with the findings of Jongman *et al*. (200) in that the sibilants are longer than the non-sibilants, and mostly with those of Behrens and Blustein (1988a) in that /θ/ is shorter than /f/. However, when the durations of /s/ and /ʃ/ are compared by taking gender into account, the duration of /ʃ/ tends to be longer than that of /s/. Post-hoc analyses using Tukey HSD indicate that no difference is found in /f/ between male and females (p>.94), between male /ʃ/ and female /s/ (p>.22), in /θ/ between male and female speakers (p>.99) and between /s/ and /ʃ/ of male speakers (p>.06). The results implies that the distance between sibilants is significantly greater in female speakers than in male speakers, and the
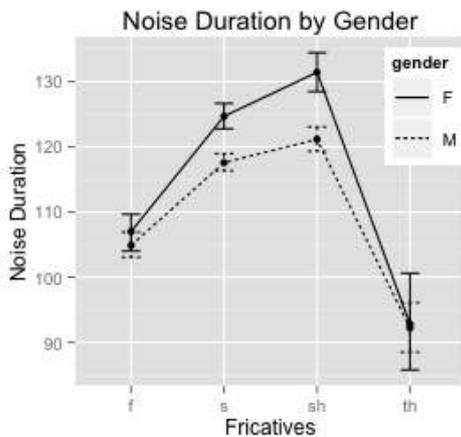

Figure 5. Noise duration

non-sibilants are likely to be distinguished by noise duration, despite the greater variability of the interdental fricatives.

3.1.4. F2 onset

The outcome of perceptual experiments on fricative consonants showed that formant information is important in discriminating among fricatives when strong spectral cues are absent (Wagner, Ernestus and Cutler 2006). Wilde (1993) observed that, for a given vowel context, F2 onset is progressively higher as the place of constriction moves back in the oral cavity. In the current study, only F2 onset values of high front vowels are examined because the vowel quality may affect greatly the F2 values. The results show that except for /θ/, the trend holds for the TIMIT data. Post-hoc analyses using Tukey HSD indicate that there is no difference between /θ/ and /f/ of female speakers (p>.94), between male /s/ and female /f/ (p>.55), between male /ʃ/ and female /s/ (p>.26), between male /ʃ/ and female /f/ (p>.23), and between male /θ/ and male /f/ (p>.07).
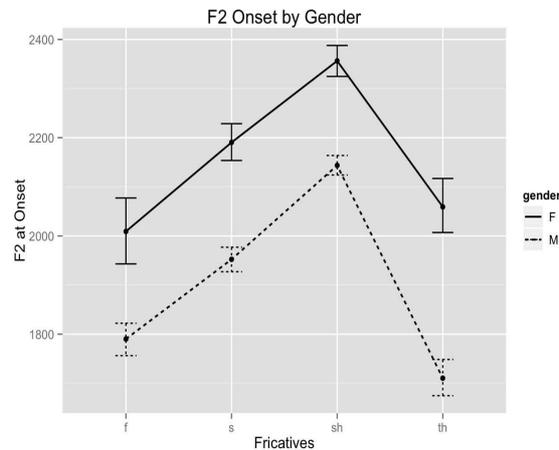

Figure 6. F2 onset

3.2 Classification

Thus far acoustic properties of voiceless fricatives are examined based on the interaction of places of articulation and gender. In general, sibilants are under greater influences of gender, whereas non-sibilants do not seem to be influenced by it. Features such as center of gravity, dispersion, duration and F2 onset are sufficient enough to discriminate sibilants from non-sibilants, and even if gender may interact in some cases, they can be used to distinguish alveolar sibilants from post-alveolar sibilants. Only few features may play a role in discriminating interdental from labiodental fricatives. In order to see how accurately voiceless fricatives can be classified, a simple

linear discriminant analysis (LDA) is conducted to predict places of articulation and gender, respectively, using the extracted acoustic features.

POA Classification: The current study conducted a linear discriminant analysis using the *lda* package in R. The explanatory variables were (1) center of gravity, (2) dispersion, (3) skewness, (4) kurtosis, (5) noise amplitude, (6) noise duration, and (7) F2 at the onset. The predictor variable was the 4 voiceless fricatives. The results are in Table 2. The overall accuracy is 85.73%. The sibilants are 88.61% correctly classified, whereas the non-sibilants are only 57.91% correctly classified. The majority of errors are from the misclassification of /Ɵ/ as [f] (error rate of 71.24%).

Table 2. Classification accuracy

	f	s	sh [ʃ]	th [Ɵ]
Accuracy	92.25%	91.12%	86.10%	23.57%

The confusion matrix are in Table 3. In Table 3, actual voiceless fricatives are presented in rows and observed fricatives are in columns. Most errors are from the misclassification of /th/ as [f].

Table 3. Confusion matrix

	f	s	sh	th
f	**1180**	18	15	66
s	59	**2576**	176	16
sh	8	158	**1029**	0
th	<u>275</u>	19	1	**91**

Except for the case of [Ɵ], the classification accuracy of voiceless fricatives into places of articulation is generally good. We now turn to the issue of gender classification.

Gender Classification: The procedure for gender classification is the same as that for POA classification, with the only difference that the predictor variable is gender. The average accuracy of gender classification is 77.67%. The data is further divided into sibilants only and non-sibilants only, and classification experiments are done on each of the divided data. In this way, we could infer that most of inaccuracy results from the classification of female speakers in non-sibilants (1.06%), as Table 4 shows.

Table 4. Classification of Gender based on all fricatives, sibilants only and non-sibilants only

	Male	**Female**	**Average**	**kappa**
All	95.53%	34.24%	77.68%	0.35
Sibilants	93.32%	52.54%	81.37%	0.50
non-sibilants	98.99%	1.06%	71.41%	0.0008

Note is that the classification of gender is biased due to the inherent imbalance between male speakers and female speakers. Thus, Kappa statistic is more appropriate than average correction rate. Kappa statistic is a measure of agreement between the model output and input labels which takes into account chance agreement. The value ranges from 0 to 1. Given Table 3 and Table 4, it is likely that female speakers' interdental fricatives are the hardest to correctly identify among the voiceless fricatives produced by either gender.

4. Discussions

Like previous studies of voiceless fricatives, the current study concentrated on four acoustic attributes: (1) spectral properties of the frication noise (*i.e.* center of gravity, dispersion, *etc.*), (2) amplitude of the noise, (3) duration of the noise, and (4) spectral properties of the transition from the fricative into the following vowel (*i.e.* F2 onset). The gender difference between the acoustic characteristics of voiceless fricatives reported in this paper can be mainly observed in sibilant fricatives. A trend is found for English males to have a longer palate than English females (Fuchs and Toda 2010). Furthermore, /s/ is made at a more retracted construction point in male speakers than in female speakers in American English (Strand 1999). Besides, female speakers utilized more acoustic spaces than male counterparts. The effect is, thus, due to both biological and sociophonetic factors. The difference between gender in non-sibilant fricatives, and even the difference between non-sibilants are minimal.

The similarity of acoustic features of non-sibilants may be attributed to the non-significant difference in the front part of the vocal tract. According to McGuire and Babel (in press), the auditory confusability of the two non-sibilant fricatives /Ɵ/ and /f/ is well-known (e.g. Miller and Nicely, 1955), and has been argued as the cause of substitution of the sounds (Labov *et al.* 1968: 93). /Ɵ/ is diachronically and synchronically instable and it is frequently substituted with its highly confusable counterpart /f/. McGuire and Babel (in press) argue that /Ɵ/ is more variable than /f/ in North American English and it is this variation that

would lead to its lack of stability in language.

There are studies that attempt to classify voiceless fricatives from a set of acoustic features. For example, Tabain (1998) obtained high classification rates for sibilants and moderate rates for non-sibilants. A Bayesian distance measure was applied to average spectra across each fricative. Classification across 5 male and 5 female speakers averaged 97% for the sibilants but only 70% for the non-sibilants. In the current study, we conducted a linear discriminant analysis. The explanatory variables were (1) center of gravity, (2) dispersion, (3) kurtosis, (4) intensity, (5) noise duration, and (6) F2 at the onset. The predictor variable was one of the 4 voiceless fricatives. The overall accuracy is 85.73%. The sibilants are 88.61% correctly classified, whereas the non-sibilants are only 57.91% correctly classified. The majority of errors are from the misclassification of /Ө/ as [f]. The result is not as good as the one reported in Tabain (1998), but given the sheer number of speakers and contextual variability, the results look promising.

Classification of places of articulation is followed by gender classification. Schwartz (1968) studied listeners' ability to identify speakers' sex from a variety of isolated voiceless fricatives. Results of his study showed that listeners were able to identify speakers' sex for the sibilants, but not for /f, Ө/. This was attributed to the higher frequencies in females' realization in comparison to males' realization of the sibilants (Fuchs & Toda 2010). The results reported in the current paper are in line with the previous study. The average accuracy of gender classification is 77.67%. And most of inaccuracy results from the classification of female speakers in non-sibilants. Thus, the classification of gender based on the acoustic properties corroborates the perceptual experiments in Schwartz (1968).

5. Conclusion

This paper examined whether there were systematic gender differences in the acoustic properties of voiceless fricatives in American English using the TIMIT corpus. The findings suggest that there are gender differences in the realization of acoustic properties and no single acoustic features may not be able to distinguish among voiceless fricatives. The findings in this paper indicate that the acoustic differences between male and female speakers are better accounted for by a mixture of biological and physical differences and macro-socio factors such as gender. The current study is distinct from most previous studies of voiceless fricatives in that while many previous studies analyzed voiceless

fricatives by extracting features from a fixed frame in carrier phrases with a limited number of speakers, the current study contributes to the existing knowledge on the acoustic analyses of fricatives by looking at those properties using a large-scale corpus that consists of more than 600 talkers and more than 2000 sentences. Further studies are in order to investigate the fricatives from the perspectives of voicing feature and dialectal or educational levels as well as contextual factors such as vowels or speech rate.

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