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INVESTIGATION OF IDENTIFICATION OF VOICELESS FRICATIVE-VOWEL SYLLABLES BY SUBJECTS WITH HIGH-FREQUENCY HEARING IMPAIRMENT

A Dissertation

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ABSTRACT

The importance of high-frequency energy as a cue for the identification of the voiceless fricatives was investigated. Five subjects were chosen on the basis of audiometric configurations characterized by a minimum of a 45 dB slope in sensitivity from 1000 cps to 2000 cps. This criterion was established to reduce or eliminate the availability of high-frequency energy cues. Sixteen syllables were formed by combining each of the voiceless fricatives [/s/, /ʃ/, /f/, /θ/] with each of the vowels [/i/, /e/, /o/, /u/]. Each syllable was presented 250 times to each subject for a total of 4000 identifications over five test sessions.

Confusion matrices were the main method of analysis. Correct identifications of the syllables were made far above chance levels. Subjects demonstrated idiosyncratic confusion patterns. The matrices revealed: (1) errors tended to divide into two groups such that /s/ and /ʃ/ were primarily confused for one another and /f/ and /θ/ were confused for one another; (2) confusions never occurred across the vowels; (3) substantially fewer confusions occurred for fricatives associated with back vowels than occurred in conjunction with the front vowels.

Based upon the assumption that these subjects were denied high-frequency spectral information, the results of the experiment are difficult to reconcile with previous studies that have emphasized the importance of high-frequency information.

Acoustic analysis of fricative spectra and a review of previous literature indicated the presence of low-frequency energy. This suggested that duration, intensity, of frequency position of such energy could have provided cues for the subjects. The differences associated with vowels suggested formant transitions as important cues for fricative identification. There was no supportable evidence which indicated that a single cue was sufficient for differentiating the voiceless fricatives. The most likely explanation for the performance of the subjects appeared to be a combination of the above parameters.

CHAPTER I

INTRODUCTION

Attempts to analyze the spectrum of speech signals to determine the acoustic parameters which influence listener perceptions took place at least as far back as the nineteenth century according to historical reviews (Pierce and David, 1958; Moses, 1964). However, the study of speech perception was severely limited because of the laborious and time consuming methods available for analysis of the speech signal. With the development of the sound spectrograph in the middle 1940's, the major limitations in instrumentation for analyzing the speech stimulus appeared to be overcome (Koenig, et. al., 1946; Licklider and Miller, 1951). Researchers began a steadily accelerating pace of investigations to determine the acoustic parameters of natural speech utterances and their relations to speech perception (Potter, et. al., 1947; Joos, 1948; Potter and Peterson, 1948).

In the early 1950's Haskins Laboratories in New York published accounts of research in speech perception using synthetic speech produced by an instrument called the pattern-playback (Cooper, et. al., 1952; Delattre,

et. al., 1955). Their main procedure was the manipulation of individual parameters of the speech signal to determine the effects on listener judgments. One of the group (Delattre, 1958) suggested that the analysis of spectrograms could only point to the possible acoustical cues for speech perception and that synthesis of the speech signal through instruments such as the pattern-playback must be used to provide verification.

Liberman (1957) in reviewing the research at Haskins Laboratory stated that the speech wave contained several simultaneous cues for a particular sound. For example, cues for identification of a stop consonant included frequency position of bursts of noise, duration of noise, nature of the onset of the noise, and the characteristics of transitions from a consonant to the succeeding vowel.

Both the acoustical parameters and the perception of fricatives have been studied by use of natural speech, distorted speech, and synthetic speech; yet our understanding of these factors is far from complete. One finding common to all of the research is the importance of high-frequency energy concentrations for perception of those sounds.

Potter, et. al., (1947) and Joos (1948) reported analysis of the fricatives in natural utterances.

Hughes and Halle (1956) isolated segments of the voiceless fricatives /ʃ/, /s/, and /f/ and presented

them to listeners for identification. They determined that the density of high-frequency energy of the spectra played an important role in perception of the fricatives. Their data showed that the major resonance for /ʃ/ occurred at or above 2000 cps and that for /s/ above 3500 cps.

Harris (1958) assessed the relative importance of cues in the friction and vocalic portions of fricative-vowel syllables. Using a tape recording-cutting-resplicing technique, she split "low-intensity, high-frequency noise" of the friction away from the "high-intensity, low-frequency periodic sound wave" of the vowel and then combined friction and vocalic portions from different syllables to form new stimuli. She presumed that the best cue would determine the listener identifications of the phonemes. She concluded that friction was important in differentiating the voiceless fricatives into two groups--/s-ʃ/ and /f-θ/. She stated that, "...the friction of /s/ and /ʃ/ provide the necessary and sufficient cues for their identification, and override whatever cues may be provided by the vocalic portions" (p. 5). She further stated that /f/ and /θ/ were differentiated on the basis of cues in the vocalic portions of the stimuli.

Heinz and Stevens (1961) used a procedure of matching speech spectra generated by an electrical model of the vocal mechanism. They generated fricatives with resonant frequencies ranging from 2500 to 8000 cps and

presented them to listeners for identification. In one condition the fricatives were presented in isolation and in a second condition they were paired with a synthetic vowel. Responses of /ʃ/ were obtained when the resonant frequency was in the vicinity of 2500 cps, /s/ when the resonant frequency was above 3000 cps, and /f/ or /θ/ for frequencies of 6500 to 8000 cps. They noted that their listeners apparently could not differentiate /f/ and /θ/ in the isolated presentations. When paired with the synthetic vowel they found that /f/ and /θ/ were apparently differentiated on the basis of the second formant transition.

The necessity of high-frequency energy for identification of the voiceless fricatives has been implied by reports of observations of identifications made by individuals with high-frequency hearing impairment. However, these reports are apparently based on clinical observation and not upon experimental evidence. Heller (1955) in discussing high-frequency hearing impairment in the 3200 to 8000 cps range said in reference to voiceless consonants that, "An appreciable loss of hearing in this range impairs the perception of these sounds and blocks their reproduction" (p. 198). Streng, et. al., (1955, p. 79), Davis and Silverman (1961, p. 188 and p. 372), Newby (1964, p. 315), and Van Riper (1964, p. 125) all stated that persons with high-frequency hearing impairment

have difficulty discriminating high-frequency consonants, which includes the voiceless fricatives.

Apparently there are no experimental studies to support this clinical observation.

CHAPTER II

EXPERIMENTAL PROCEDURE

The Purpose of the Experiment

The purpose of this study was to investigate the identification of voiceless fricative-vowel syllables by subjects with high-frequency hearing impairment.

Subjects

The subjects were five male adults with high-frequency, sensory-neural hearing impairment. Their age range was from twenty-five to fifty-five years of age. The hearing impairment reportedly had its onset in adulthood as a result of acoustic trauma and had been present from five to twenty years. American English was the native language for all subjects.

The results of audiological evaluation of the subjects are presented in Appendix A. The evaluation included pure-tone air and bone conduction thresholds, speech reception thresholds, speech discrimination scores, and the SISI test.

The pure-tone thresholds for frequencies from 250 cps to 1000 cps were not poorer than 25 dB (re: 1964

ISO Standard). The sensitivity for 2000 cps and all higher frequencies was at least 45 dB poorer than the sensitivity at 1000 cps. The bone conduction thresholds were within 5 dB of the air conduction thresholds for all frequencies in which sensitivity was within limits of the bone conduction equipment.

The sensitivity criteria were selected in an effort to eliminate or substantially reduce the availability of high-frequency energy as a cue. It has already been indicated that several studies have found the frequencies from 2000 cps upward to be the important frequencies for the perception of fricatives. In addition to the frequency data there has been work on the intensity relations which occur between fricatives and vowels. Sacia and Beck (1926) reported that the power of voiceless fricatives is considerably less than that of the average vowel. They found /ʃ/ to be the most powerful of the voiceless fricative group with /s/, /f/, and /θ/ following in descending order. Fairbanks and Miron (1957) made an extensive study of /s/ combined with vowels and found that the consonant to vowel ratio had a median value of -14 dB.

The speech stimuli used in the present study were presented through a speech audiometer-earphone system at a level above the SRT which each subject designated as his comfort level. In every instance the intensity level chosen by the subject was less than his threshold

value for 2000 cps and higher frequencies. The combination of the hearing impairment, the fricative to vowel intensity ratio and the level of presentation of materials should have reduced or eliminated the availability of high-frequency cues contained in the fricatives.

Materials

Preparation of the Materials

Sixteen consonant-vowel syllables formed by combining each of the fricatives [/ʃ/, /s/, /f/, /θ/] with each of the vowels [/i/, /e/, /o/, /u/] were uttered by a male talker into an Altec 682A dynamic microphone in the control room of a two-room sound suite and recorded through an Ampex PR-10 tape recorder in the test room of the suite. The syllables were preceeded by a carrier phrase and the vowel of each syllable was monitored to peak at zero on a VU meter.

The carrier phrases were cut from the tape and the remaining sixteen syllables constituted the master tape. The syllables were each re-recorded fifty times from the master tape onto a second tape called the test tape. The syllables were recorded on the test tape in a quasi-random manner such that no syllable immediately succeeded itself. There was a four second interval between syllable presentations.

A 1000 cps pure-tone approximating the median peak value of the sixteen syllables was recorded on the test

tape and was used to calibrate the VU meter of a Grason-Stadler speech audiometer to a zero reading prior to presentation of the syllables through the speech audiometer-earphone system.

A spoken cue recorded on the test tape after each ten syllables informed the listener of the number of the next blank to be completed on an answer form.

<u>Analysis of the Syllables</u>

The identifiability of the syllables was tested by administering the test tape to three subjects whose sensitivity for pure-tones from 250 cps through 8000 cps was no poorer than 5 dB (re: 1964 ISO Standards). The syllables were presented to the preferred ear of the subject at an arbitrary level of 30 dB above the SRT. The syllables were identified correctly by these subjects in 97% of the trials.

Acoustical parameters of the syllables; intensity, frequency, and duration, were analyzed through use of a Kay Sono-Graph (Model 6061-A) and a General Radio Level Recorder (Type 1304-B). The results of the analysis are shown in Appendix E. The lowest major resonance of the fricatives and the frequency positions for the onset and termination of the second and third formants of the vowels were obtained through spectrographic analysis. The results were in agreement with the data provided in several experimental studies (Hughes and Halle, 1956; Lehiste and Peterson, 1961). The duration of the

syllables was determined by measurement of spectrograms and tracings on the level recorder. The two procedures yielded equivalent results. The durations were in agreement with data provided by House (1961). The fricative-to-vowel intensity ratios (peak-to-peak) were derived from the level recorder tracings. The ratios for syllables containing the /s/ fricative were in agreement with results of Fairbanks and Miron (1957). There were no known experimental studies of fricative-to-vowel intensity ratios which included the other voiceless fricatives.

The analysis indicated that the characteristics of the talker were essentially similar to those of normal talkers in other studies.

Presentation of the Stimuli

Prior to the first test session a printed card bearing the orthographic representations of the closed set of sixteen syllables was given to the subject. He familiarized himself with the printed representations and wrote them on a practice answer form as the investigator uttered the syllables for him in a face-to-face situation. The investigator was not the talker used on the tapes.

When the subject had demonstrated an understanding of his task of writing the orthographic representation for each syllable presented he was seated at a writing

desk in the test chamber of a two-room sound-treated suite. A numbered answer form (see Appendix B) and several pencils were given to him.

The subject was informed that the words which he had practiced writing would be presented to him through an earphone and that his task would be to write each word in the appropriate blank even if it was necessary to guess. The printed card bearing the orthographic representations of the syllables was left with the subject for reference.

The syllables on the test tape were then presented monaurally through the speech audiometer-earphone system at a comfort level above the speech reception threshold. This was dictated by the judgment of each subject as to what was comfortable for him. All subjects had bilateral hearing losses and the ear with the best sensitivity for pure-tones was chosen as the test ear. All 800 syllables were presented in each test session. A brief rest was allowed after each presentation of 200 syllables. One test session took approximately one and one-half hours.

Five test sessions were conducted with each subject. The 800 syllables were arbitrarily divided into groups of 200 syllables and these groups were presented in different orders to a subject in each test session.

No information feedback was provided for the subjects during the course of the experiment because of the

desire to study responses which depended only upon the stimuli and the internal criterion established by the subject (Carterette, et. al., 1966; Goldiamond, 1964).

CHAPTER III

RESULTS

Individual Subjects

Table I shows the percentage of correct syllable identifications made by each subject in each test session. Since there were 16 response alternatives for each stimulus, a correct response could occur by chance once in 16 trials (1/16). A one-tailed Chi-square analysis based on the 1/16 probability showed that 67 correct responses (8.3%) to 800 stimuli were sufficient to exceed the .01 level of significance. All subjects made correct identifications far above this level.

The responses made by each subject in each test session were consolidated in the confusion matrices of Appendix D. The matrices were plotted to show fricative confusions within each of the four vowel categories. This type of plot was possible because the subjects never demonstrated a confusion across vowels.

Since confusions occurred only for the fricative portions of syllables, a one-tailed Chi-square analysis based on a 1/4 probability was performed. The .01 level of significance was attained with 229 correct

identifications (28.6%) to 800 stimulus presentations. The scores of Table I show that even with the probability basis revised from 1/16 to 1/4 all subjects made correct identifications far in excess of the .01 level of statistical significance.

Table I.--Percentage of correct syllable identifications in each test session for each subject and for the group. N=800 stimuli per session for each subject.

	Subjects					
	AA	RD	RI	LB	LL	Group Total
Test Session						
1.	75%	69%	74%	79%	72%	74%
2.	73%	72%	79%	83%	75%	76%
3.	81%	74%	86%	85%	79%	81%
4.	84%	73%	89%	87%	80%	83%
5.	80%	76%	93%	86%	80%	83%

Table II shows the percentage of correct responses made to each fricative by each subject over the five test sessions. The vocalic portions of the syllables were confounded in the grouping of the fricatives. A one-tailed Chi-square analysis based on a 1/4 probability showed that 283 correct identifications (28.3%) to the 1000 presentations of each fricative were sufficient to attain the .01 level of significance.

The over-all response patterns in terms of percentage correct, established by the subjects showed little

deviation from session-to-session. Table I shows there was little difference in the number of correct responses either across sessions or within subjects. Although the results of the last three test sessions were quite similar in reflecting stability of responses, only the last test session was chosen for detailed analysis. These analyses are presented following Table II.

Table II.--Percentage of correct fricative identifications by each subject in all five test sessions. Fricatives were grouped with the vowel components of the syllables confounded. Each fricative was presented 1000 times to each subject.

	Stimulus Fricative			
	/s/	/ʃ/	/f/	/θ/
Subject				
AA	95%	99%	82%	38%
RD	67%	73%	66%	85%
RI	90%	77%	77%	92%
LB	86%	91%	78%	81%
LL	74%	95%	78%	61%

The specific fricative confusions of each subject were plotted in subset confusion matrices according to vowel categories. Matrices were plotted for only those vowel groups in which a subject demonstrated consistent and marked fricative confusions.

By visual inspection, a consistent confusion was one which persisted through the last three sessions. A

marked confusion was one in which the subject correctly identified a specified fricative less than 45 times in fifty presentations. This approach was used rather than a strict adherence to a statistical criterion. If failure to reach the .01 level of statistical significance for a Chi-square based on a 1/4 probability were selected as the criterion, only syllables with fewer than 21 correct identifications would have been analyzed. Use of such a criterion would have resulted in analysis of approximately one syllable per subject.

<u>Subject AA</u>

Table III shows this subject had confusions for certain fricatives within three vowel categories. In each matrix there are confusions for the fricative /θ/. Confusions for /f/ occurred only in the /i/ matrix and there were seldom any confusions for the /s/ fricative.

There was 100% response of /fe/ for /θe/. This trend was shown for the last four sessions. Correct responses to the /fe/ stimulus were made in 98% to 100% of the trials in the last three test sessions.

The response of /si/ for /fi/ was made more often by Subject AA than by any other subject.

He was the only subject to make a marked /so/ for /θo/ confusion. No other subject made a marked confusion in the /o/ vowel category.

Table III.--Subset confusion matrices for Subject AA with data grouped according to vowel categories. The data represent the last test session N=50 per syllable.

		Response											
		/i/				/e/				/o/			
		/s/	/ʃ/	/f/	/θ/	/s/	/ʃ/	/f/	/θ/	/s/	/ʃ/	/f/	/θ/
Stimulus	/s/	43	5	2		48		2		50			
	/ʃ/		50			1	49				50		
	/f/	24	1	22	3	1		49				50	
	/θ/	4		22	24			50		34		6	10

Inspection of the confusion matrices for the five sessions (Appendix D) showed that this subject had a unique response pattern to the syllable /θi/. He responded with /si/ 60% of the time in the first session and increased this to 84% in the second session. In the third session he abruptly changed his response to 76% correct identifications of /θi/. In the last two sessions he changed to an approximate 50% response between /fi/ and /θi/. In other words, throughout the five sessions he moved from an incorrect response of /si/, to a correct response of /θi/, and then in the last two sessions divided his responses between /fi/ and /θi/. This was the only occurrence in the entire experiment of a multiple shift in response choices.

Subject RD

This subject had confusions for more syllables

than any other subject. Table I shows that he had the fewest correct identifications in every session.

Table IV shows that confusions occurred within three vowel matrices. The majority of confusions were in the front vowel matrices. Every fricative was confused in the /e/ matrix and all except /ʃ/ were confused in the /i/ matrix.

Table IV.--Subset confusion matrices for Subject RD with data grouped according to vowel categories. The data represent the last test session. N=50 per syllable.

	Response											
	/i/				/e/				/u/			
Stimulus	/s/	/ʃ/	/f/	/θ/	/s/	/ʃ/	/f/	/θ/	/s/	/ʃ/	/f/	/θ/
/s/	19	30	1		23	23	2	2	40	10		
/ʃ/	2	48			34	14	2			50		
/f/	14	5	21	10	1	1	36	12			50	
/θ/	2		19	29		1	13	36	3			47

There was less difficulty for the back vowels as evidenced by the single confusion in the /u/ group and the lack of appreciable confusion in the /o/ group.

The fricative /s/ was confused in all three matrices, /f/ and /θ/ stimuli were confused in two matrices, and /ʃ/ was confused only in the /e/ matrix.

The majority of confusions followed a pattern in which the /s/ and /ʃ/ syllables were confused with one another and the /f/ and /θ/ syllables were confused with one another. An exception to this pattern was shown in the responses to /fi/. The incorrect responses for this syllable were divided almost equally between /si/ and /θi/.

<u>Subject RI</u>

Inspection of Table I revealed that this subject demonstrated the greatest improvement in correct identifications from the first to the last test session. His percentage of improvement was more than twice that of any other subject.

The confusions which he made in the last test session are shown in Table V.

Table V.--Subset confusion matrices for Subject RI with data grouped according to vowel categories. The data represent the last test session. N=50 per syllable.

	Response							
	/i/				/e/			
Stimulus	/s/	/ʃ/	/f/	/θ/	/s/	/ʃ/	/f/	/θ/
/s/	49	1			46		2	2
/ʃ/	2	43	5		4	46		
/f/	2		33	15			33	17
/θ/			2	48			3	47

The primary confusions were for the fricative /f/ associated with front vowels. He had predominately correct identifications for these stimuli and the incorrect responses were almost exclusively /θ/. The fricatives were correctly identified in conjunction with the back vowels on all except three trials.

Subject LB

Table VI shows the confusion matrices for this subject.

Table VI.--Subset confusion matrices for Subject LB with data grouped according to vowel categories. The data represent the last test session. N=50 per syllable.

		Response /i/				Response /e/			
		/s/	/ʃ/	/f/	/θ/	/s/	/ʃ/	/f/	/θ/
Stimulus	/s/	38	7		5	46	2		2
	/ʃ/	5	44		1	8	40		2
	/f/	13	3	18	16			44	6
	/θ/	3	3	5	39			14	36

The responses to syllables containing the fricative /f/ were spread throughout the /i/ matrix. The responses to the /fi/ stimulus were almost evenly divided between /fi/, /θi/, and /si/. This was the only occurrence of a nearly evenly divided three-way response distribution for a stimulus.

Inspection of the response pattern revealed a trend to confuse /s/ and /ʃ/ with one another and /θ/ and /f/ with one another. The exception, as noted above, was the response of /si/ for /fi/. The confusion of /si/ for /fi/ was evidenced by three subjects although in varying degrees.

Subject LL

Table VII indicates that this subject had consistent confusions in only the front vowels. Except for two errors he had perfect identifications of fricatives paired with back vowels.

Table VII.--Subset confusion matrices for Subject LL with data grouped according to vowel categories. The data represent the last test session. N=50 per syllable.

		Response							
		/i/				/e/			
		/s/	/ʃ/	/f/	/θ/	/s/	/ʃ/	/f/	/θ/
Stimulus	/s/		50			45	4	1	
	/ʃ/		50			2	48		
	/f/	6	24	2	18			50	
	/θ/		4		46			50	

He always responded /ʃi/ to either of the /ʃi/ or /si/ stimuli and always /fe/ to the /fe/ or /θe/ stimuli. This resulted in the appearance of correct identification of one stimulus and complete misidentification of the other.

He rarely identified the /fi/ stimulus but responded primarily with /ʃi/ and /θi/. This was the only occurrence of the response pattern being divided equally when one of the members was not a correct identification. Also the responses of /ʃi/ for /fi/ were a deviation from the tendency to confuse /s/ and /ʃ/ for one another and /f/ and /θ/ for one another.

Inspection of the confusion matrices of Appendix D indicated an unusual pattern which seemed to have occurred in his responses to /si/. In the first test session he correctly identified /si/ on 48% of the trials and misidentified it as /ʃi/ 52% of the time. Thereafter, he increasingly responded /ʃi/ to the /si/ stimulus until in the fifth session he always responded /ʃi/.

Group Results

Even though the unique response patterns demonstrated by the subjects seemed to generate the most information, group analysis was also undertaken in an attempt to further delineate the findings.

Table VIII shows the percentage responses of the group to each fricative stimulus in the last test session.

The pattern displayed in the matrix shows the tendency to confuse /s/ and /ʃ/ for one another and /f/ and /θ/ for one another.

Table VIII.--Confusion matrix demonstrating combined responses of subjects in the last test session. The data were grouped according to the fricative components of the syllables with vowels confounded. N=1000 per fricative.

		Response			
		/s/	/ʃ/	/f/	/θ/
Stimulus	/s/	83.6%	13.5%	1.8%	1.1%
	/ʃ/	6.4%	92.6%	.7%	.3%
	/f/	6.1%	3.4%	80.5%	10.0%
	/θ/	5.8%	.8%	18.7%	74.7%

Table IX shows a ranking of correct fricative identifications when associated with the different vowels. There was not a consistent fricative rank order across vowels. It is interesting to note the fricative /f/ was the only one which demonstrated consistency in rank position in that it was highest ranked with three of the vowels. However, it was the lowest ranked fricative with /i/.

The fricatives were identified correctly more often when associated with back vowels than with front vowels.

It is remarkable that the /f/, which was not particularly well identified when vowels were confounded (see Table II), was identified nearly perfectly with the vowel /o/ and perfectly with /u/.

Table IX.--Cumulative correct responses of all subjects in the last test session with fricative components ranked under each of the vowels. N=250 per syllable.

	Vowels			
	/i/	/e/	/o/	/u/
Fricatives	/ʃ/ 94.0%	/f/ 84.0%	/f/ 98.8%	/f/ 100.0%
	/θ/ 74.0%	/s/ 83.2%	/ʃ/ 98.4%	/ʃ/ 99.2%
	/s/ 59.6%	/ʃ/ 78.8%	/s/ 96.4%	/θ/ 95.6%
	/f/ 38.4%	/θ/ 47.6%	/θ/ 81.2%	/s/ 95.2%

Information from the group data is quite limited in that the idiosyncratic responses of one or two of the subjects so heavily weighted the group result. For example, the percentage for the /s/ in the /i/ matrix of Table IX is spuriously low due to the responses of Subject LL. He never responded correctly to /si/ in the last session, thereby lowering the group average. The same is true for Subject AA in regard to /θe/.

CHAPTER IV

DISCUSSION

Research reports and clinical tests have indicated the importance of high-frequency cues for identification of voiceless fricatives. The subjects in the present study, theoretically denied the use of these cues, evidenced little difficulty in correctly identifying the majority of the 16 voiceless fricative-vowel syllables. Obviously the major information bearing elements were other than high-frequency cues to enable these individuals to correctly identify the syllables.

A voiceless fricative, as defined by Strevens (1960), is essentially a spectrum of aperiodic random noise. Joos (1948) in commenting on this aperiodicity presented an analogy comparing the mottled appearance of the random distribution of energy of the fricatives, as seen on spectrograms, with the distribution of moisture on dry pavement a few minutes after a shower started: no matter what interesting pattern was formed, it did not predict anything about another pattern on another piece of pavement. Strevens (1960) found that amplitude cross-sections of spectrograms of the fricatives varied considerably. One single cross-section per fricative yielded apparently

helpful information about peaks of energy. A second cross-section from the same utterance, however, almost invariably gave information that conflicted in details with the previous analysis. These differences presumably resulted from the aperiodic nature of the fricative. Hughes and Halle (1956) found that discrepancies among the spectra of a given fricative as spoken by different speakers in different contexts were quite large. However, they stated that differences among three classes of fricatives (labial, dental, and palatal) were quite consistent, particularly for sounds spoken by a single speaker.

There are a number of parameters besides high-frequency energy in the spectrum of voiceless fricatives which can be suggested as potential cues for identification of the voiceless fricatives.

Although rarely stressed as containing important cues, the presence of energy below 2000 cps has been demonstrated in analysis of the fricative spectra.

Hughes and Halle (1956) presented acoustical analysis of the fricatives which indicated that energy was present below 1000 cps. Delattre (1958) remarked that energy for /f/ and /θ/ spread throughout the entire spectrum on Kay spectrograms. Strevens (1960) demonstrated spectrographic evidence that energy was present as low as 1500 cps for /f/, 1400 cps for /θ/, and 1600 cps for /ʃ/. Heinz and Stevens (1961) found in generating

synthetic fricatives that some of the /f/ spectra they were attempting to match were characterized by broad low-frequency noise in addition to the high-frequency peaks and for those sounds it was necessary to add low-frequency noise electrically in order to obtain good agreement with the measured spectra.

Strevens (1960) and Hirsh (1966) indicated the voiceless fricatives have spectrums of varying widths and indicated that the sounds could differ in terms of both center frequency of the spectrum and in spectrum width. Strevens found that /f/ and /θ/ were characterized by a wide spectrum covering a range from some 5000 to 6000 cycles while /s/ and /ʃ/ had a narrower spectrum covering some 3000 to 4000 cycles.

Hirsh (1966) stated that the voiceless fricatives were of different durations and that the durational characteristics were probably important for distinguishing between them.

Sacia and Beck (1926) and Strevens (1960) found that the voiceless fricatives differed in intensity. The /ʃ/ was the most intense sound of the group with /s/, /f/, and /θ/ following in descending order.

As for evidence in regard to frequency cues, the results of studies by Miller and Nicely (1955) and Hughes and Halle (1956) are applicable. Miller and Nicely presented syllables to subjects in various conditions of masking and filtering. In the condition in

which a signal-to-noise ratio of +12 dB and a band-pass of 2000 to 5000 cps were used (see their Table XIV), the subjects were impaired in their ability to identify the voiceless fricatives. More confusions occurred for /f/ and /θ/ than for /ʃ/ and /s/. The /f/ and /θ/ confusions occurred across consonant classes as well as within class. Identifications of /ʃ/ and /s/ were impaired in comparison to those of band-pass conditions which had a lower cut-off frequency, but were still quite high. The same trend of wide spread confusion for /f/ and /θ/ with much better identification of /s/ and /ʃ/ was noted for all higher pass-band conditions.

Hughes and Halle (1956) had noted that when responses of their subjects were shown as functions of frequency position of the maximum of the spectrum that /f/ identifications showed a sharp drop for peaks located above 2000 cps and /s/ judgments increased for peaks above 4000 cps. The /ʃ/ judgments were greatest when peaks occurred in frequencies between 2000 and 4000 cps.

The results of the Miller and Nicely study and the Hughes and Halle study suggest that high-frequency energy cues are not as important for identification of /f/ and /θ/, as they are for /s/ and /ʃ/ identifications.

High-frequency energy cannot be vital for identifications of all of the voiceless fricatives according to results of the Miller and Nicely study for conditions which passed frequencies below 2000 cps. In the condition

of a signal-to-noise ratio of +12 dB and a band-pass of 200 to 1200 cps (see their Table X) the subjects were able to identify the voiceless fricatives far above chance levels. Better identifications occurred for /f/ than for the other voiceless fricatives. A similar result was obtained with a signal-to-noise ratio of +12 dB and a band-pass of 200 to 600 cps (see their Table IX).

In both of the latter conditions /f/ and /θ/ were identified correctly more often than in conditions in which only frequencies above 2000 cps were passed.

The data of Miller and Nicely strongly suggests that the importance of low-frequency energy cues for the fricatives can not be minimized. The results of the present study could be partially explained on the basis of center frequency and width of the energy bands in the spectrum. This possibility draws support from a discussion by Swets (1963) in which he inferred the importance of central or cognitive factors in frequency selectivity. He suggested that the strategy of listening that is adopted by an observer for a particular task is closely linked to the number, frequency locations, and widths of critical bands which are operative. It is not inconceivable that the hearing impaired subjects were able to adopt a strategy in which they were able to use low-frequency band-widths for identification purposes.

Duration has been found to be a cue for differentiating among consonant classes (Barrs, 1963). There is apparently no definitive study of the cue value of duration for distinguishing between the voiceless fricatives. However, as Hirsh (1966) stated, and as was found from acoustical analysis of the syllables in this study, there are durational differences between the voiceless fricatives. The possibility exists that these subjects could have used durational cues to differentiate the voiceless fricatives.

The possibility of intensity as a cue for differentiating among the fricatives has not been subjected to extensive investigation. Hughes and Halle (1956) indicated that intensity differences measured throughout the fricative spectrum can be used to differentiate among the /f/, /s/, and /ʃ/. Some of the problems in analyzing the intensity characteristics of the fricatives were indicated by Strevens (1960). He found that voiceless fricatives which occurred in connected speech rarely gave usable spectral information. He attributed this to two factors: (1) the over-all acoustic energy of the voiceless fricatives is generally much lower than the stressed vowels which serve as reference points for adjusting the signal level on the spectrograph; and (2) the duration of the fricatives is often so short that the quantity of pattern available is inadequate.

The intensity range of the spectrograph and the electrically sensitive paper upon which the patterns are depicted is so restricted that when the vowels are used to monitor the input signal to the instrument, only the most intense energy of fricatives will appear upon the spectrogram. This tends to de-emphasize the presence of the low-frequency energy of the voiceless fricatives.

Regardless of whether intensity, in and of itself, is a cue, the subjective report of the subjects indicated that there was sufficient intensity available to identify the presence of the fricative portion of the syllable. The subjects were asked to describe what they heard when the syllables were presented. Each of them indicated that he heard a "hiss" or "buzz" before the onset of the vowel.

The validity of the subject report was explored after completion of the main experiment. A test tape of the syllables was made in which the friction portion was removed from the tape. When the test tape of only the vocalic portion of the syllables was presented to the subjects for identification, they immediately reported the absence of the "hiss" or "buzz". While they were able to identify the vowels, they were unable to identify the voiceless fricative. When forced to guess they responded on a chance basis.

This subjective report and the inability to identify the fricatives without the "hiss" or "buzz" supports the

contention of usable cues in the low-frequency energy spectrum of the fricative and is in accord with a finding by Heinz and Stevens (1961) that identifications of /f/ and /θ/ were enhanced by the addition of low-frequency noise to their synthesized speech stimuli.

On the basis of their audiometric profiles; pure-tone thresholds, speech scores, and SISI scores, the subjects appeared to constitute a relatively homogeneous group. From inspection of the confusion matrices of Appendix D it is obvious that individual subjects presented unique and idiosyncratic response patterns.

Considering syllables rather than fricatives for the moment, the differences in subjects can be demonstrated by their responses to /fi/ in the last test session. While this stimulus was confused by all subjects, it is apparent that a different pattern of confusions was demonstrated by each subject. Subject LB identified it almost equally as /fi, /θi/, and /si/. Subject RD identified it correctly on 21 trials but confused it with /si/ 14 times and /θi/ 10 times. Subject AA confused /si/ for /fi/ on nearly half of the trials and Subject RI misidentified it 15 times as /θi/. Subject LL only identified the stimulus correctly on two trials. He confused it with /ʃi/ 24 times and /θi/ 18 times.

This was the only syllable that showed such high confusion on the part of all subjects. It is not known whether these results reflect inherent properties of the

stimulus or an artifact caused by characteristics of articulation by the talker or tape recording procedure. However, listeners with normal sensitivity did not experience difficulty identifying the syllable.

The fricative confusions tended to divide into two groups. The /s/ and /ʃ/ fricatives were primarily confused for one another and /f/ and /θ/ were confused for one another. A similar grouping of /s-ʃ/ and /f-θ/ was demonstrated in the data of Miller and Nicely (1955) and Harris (1958).

While the analysis by and large showed the tendency of the responses to fall conveniently into the grouping pattern, there were fricative confusions that occurred across these groupings. The majority of cross group confusions involved confusions of /s/ with /f/ or /θ/. The /ʃ/ was seldom involved in these cross group confusions except in the case of Subject LL who confused /ʃ/ for /f/ in association with the vowel /i/.

The /ʃ/ was also outstanding in the Miller and Nicely (1955) study. It was the most highly identifiable of the voiceless fricatives in all of their conditions in which only frequencies above 2000 cps were passed by the filter. It was not so well identified in the low-pass conditions but was still most often confused with /s/. The results of the present study were essentially in agreement with the findings of Miller and Nicely. The

/ʃ/ was the most highly identifiable fricative in the grouped data of the present study (see Table VIII).

The confusions of /s/ with /f/ or /θ/ were apparent in the low-frequency band-pass conditions of Miller and Nicely as well as the present study. It may be that the characteristics of /ʃ/ and /s/ are sufficiently similar that they are confused for one another but are sufficiently different that /ʃ/ is less often confused with /f/ or /θ/. There are several possible cues which could be responsible for such confusion patterns. Since /ʃ/ is the most intense of the voiceless fricatives, it may be that intensity is the overriding cue for identification of /ʃ/. Inspection of the spectrograms of the syllables used in the present study showed that the /ʃ/ was of longer duration that the other voiceless fricatives. Therefore, duration may be the overriding cue for differentiations. Still another possibility is that the combination of intensity and duration is sufficient to differentiate /ʃ/ from the other voiceless fricatives.

So far only the spectral properties of the fricatives themselves have been considered as potential cues for their identification. It has been demonstrated, however, that frequency and temporal characteristics of phonemes vary as a function of their phonetic environment (House, 1961; Lehiste and Peterson, 1961). Such variations in vowels have been deemed important cues for identification of the adjacent consonant (Wang and

Fillmore, 1961). Most of the emphasis in regard to consonant-vowel interaction has been on changes in frequency position of formant energy over time (transitions). The importance of the second formant transition for consonant identification has been emphasized by several researchers (Liberman, et. al., 1957; Heinz and Stevens, 1961; Lehiste and Peterson, 1961).

The results of the present study could be partially explained on the basis of differences in formant transitions among the vowels. The fricatives were more often confused when associated with the front vowels /i/ and /e/ than they were with the back vowels /o/ and /u/. Inspection of the spectrograms of the syllables showed that the second formants of /i/ and /e/ originated in frequencies below the target position of the vowel and changed in an upward direction over time. The second formants of the /o/ and /u/ originated at frequencies above the target position and showed downward bends toward the target position. Since the front vowel transitions traveled up toward frequencies which were in the impaired region for the subjects, it is probable that the cues from the transitions were distorted or eliminated and resulted in confusions in identifications of fricatives associated with these vowels. On the other hand, the transitions of the back vowels occurred primarily in the frequency range in which the subjects appeared to demonstrate normal

sensitivity. They should have been better able to utilize the cues in these transitions for fricative identifications.

The high identification of fricatives associated with the front vowels and the confusions which occurred in conjunction with back vowels suggests that the transition cues alone were not sufficient for identification of the fricatives. This was further indicated by results of the lack of correct identifications by the subjects when the "frictionless" syllables were presented to them. It would seem that the combination of low-frequency energy of the fricatives and the second formant transitions of the vowels may have been responsible for the identifications by the subjects.

The postulation that formant transitions figure prominently in identification of each voiceless fricative is contrary, in part, to previous studies (Harris, 1958; Heinz and Stevens, 1961) which indicated that formant transitions were important cues for identification of /f/ and /θ/ but not for /s/ and /ʃ/. Heinz and Stevens stated that second formant transitions were the most important for differentiating /f/ and /θ/. Harris did not specify any particular formant as the most important.

Inspection of Harris's results (see her Fig. 2) indicated that the subjects were inaccurate in their identifications of /f/ and /θ/. Both /f/ and /θ/ were identified primarily as /f/ when associated with /f/

vocalic portion. When associated with any other vocalic portion both /f/ and /θ/ were identified primarily as /θ/. A greater number of misidentifications of the fricative portions of the syllables occurred when they were paired with /o/ and /u/ vocalic portions than when they were paired with /i/ and /e/ vocalic portions. This is contrary to the findings of the present study which indicated that a greater number of consonant confusions occurred in conjunction with the front vowels.

The apparent contradiction in results may suggest that the spectral envelope of the stimulus is an important determinant of identifications. The results of the present study could be explained on the basis of information contained in the spectral envelope available to the subjects. Distortion of cues contained in the natural speech envelope could conceivably have occurred from the techniques utilized by Harris and influenced her results.

Schatz (1954) used a procedure similar to that of the Harris study to investigate the perception of voiceless stops. She found that her combinations yielded extremely unnatural sounding syllables in which the consonants did not closely resemble any naturally produced English sounds. This finding could be interpreted as resulting from disruption of the spectral envelope of the stimuli. If the Harris stimuli suffered from a similar effect, it is possible that the characteristics

of the /o/ and /u/ vowels were distorted more than those of /i/ and /e/.

There is evidence that /i/ and /e/ differ from /o/ and /u/ not only in formant frequency position, but also in temporal characteristics. Lehiste and Peterson (1961) showed that /e/ has a long glide as its first element while /o/ has a short steady state target as the first element and a long glide as the second element. They also showed that the initial transitions of /i/ are usually almost twice as long as those of /u/. The shorter transition of /u/ and the short steady state of /o/ could have been distorted more by the Harris procedure than were the characteristics of /i/ and /e/.

In addition to the main experiment, the subjects participated in a forced-choice fricative identification from paired stimuli (called experiment II). Any syllable which was confused by a subject for the stimulus syllable on 10% or more of the trials in the five test sessions was paired with the stimulus syllable for the forced-choice task. The subjects were required to decide if the first or second member of the presented pair contained the sound equivalent of an orthographic symbol for that trial (see Appendix C). The results to the forced-choice task (see Appendix G) were essentially the same as the main experiment.

One interesting observation is that when the composition of the syllable pair consisted of a stimulus

which had been misidentified 100% of the time as the other member of the pair, the subjects responded to either member of the pair on an equal basis in the forced-choice task (for example see the responses of Subject LL to /si-ʃi/ and /ʃi-si/). The response patterns of the main experiment taken at face value looked as though one member of the pair was identified correctly while the other was entirely misidentified. The correct interpretation, as more clearly shown in the paired task, is that the subjects could not differentiate these fricatives. The main experiment indicated a bias to always choose the same fricative for a response to either of the stimuli. When syllables were paired, it is obvious that the subjects were actually responding near chance levels.

The other interesting observation is the nearly complete elimination of confusions across the /s-ʃ/ and /f-θ/ divisions. Apparently the subjects could differentiate across these divisions when members of the different divisions were paired (for example see Subject LB's responses to /fi-si/ and Subject AA's responses to /θo-so/).

From the results of the experiment and preceding discussion it is apparent that the information regarding the perceptual cues for the voiceless fricatives is still incomplete. If the assumption is accepted that high-frequency energy available to these

subjects was reduced or eliminated, further research is needed to explore the critical perceptual cues of the voiceless fricatives.

The apparent contradictions between the present study and that of Harris suggests an area for further investigation. The use of synthetically generated syllables would appear to be one means to resolve the question of the contribution of the fricative portion and the vocalic portion to the identification of the voiceless fricatives. This procedure should provide greater control of the stimuli and eliminate the difficult problems and artifacts of segmentation of the syllable through inexact and laborious procedures such as that utilized by Harris.

Another pertinent area of investigation is the quantification of the contribution of the information contained in the transitions for the identifications of voiceless fricative-vowel syllables. From the results of this study it was suggested that the information contained in the transitions was not sufficient to enable the subjects to identify the voiceless fricatives. Determination of this was not the primary objective of the present study. An approach to this problem would be to make successive cuts in the stimulus beginning at the point at which the formants attained their target position and continuing backward toward the onset of the vowel until subjects made identifications

at a specified level. The appropriate methodology might be a forced-choice accuracy indicator task as outlined by Goldiamond (1958). In this task adjoining segments of the distorted syllable would be presented in pairs to subjects for identification. This procedure could also provide information about the temporal resolving power of the spectral envelope by the subjects.

An area that appears to be overdue for re-evaluation and investigation is the contribution of low-frequency energy in the fricative spectra to their identification. One approach to this problem would be to present isolated segments of synthetic fricatives to listeners for identification. These segments would be constructed by matching the low-frequency energy of the spectra of natural speech. Deviations from these matched spectra could then be introduced through changes in the parameters of duration, intensity, and band-widths or combinations of these parameters to determine the influence on listener judgments.

CHAPTER V

SUMMARY

The importance of high-frequency energy as a cue for the identification of the voiceless fricatives was investigated. Five subjects were chosen on the basis of audiometric configurations characterized by a minimum of a 45 dB slope in sensitivity from 1000 cps to 2000 cps. The criterion was established to reduce or eliminate the availability of high-frequency energy cues. Sixteen syllables were formed by combining each of the voiceless fricatives /s/, /ʃ/, /f/, /θ/ with each of the vowels /i/, /e/, /o/, /u/ . Each syllable was presented 250 times to each subject for a total of 4000 identifications over five test sessions.

Confusion matrices were the main method of analysis. Correct identifications of the syllables were made far above chance levels. Subjects demonstrated idiosyncratic confusion patterns. The matrices revealed; (1) errors tended to divide into two groups such that /s/ and /ʃ/ were primarily confused for one another and /f/ and /θ/ were confused for one another; (2) confusions never occurred across the vowels; (3) substantially fewer confusions occurred for fricatives associated with back

vowels than occurred in conjunction with the front vowels.

Syllables consistently confused with the stimulus were paired with the stimulus in a forced-choice identification task. The results generally supported the findings of the main experiment except that confusions across the /s-ʃ/ and /f-θ/ divisions were essentially eliminated.

Based upon the assumption that these subjects were denied high-frequency spectral information, the results of the experiment are difficult to reconcile with previous studies that have emphasized the importance of high-frequency information.

Acoustic analysis of the fricative spectra and a review of previous literature indicated the presence of low-frequency energy. This suggested that duration, intensity, or frequency position of such energy could have provided cues for the subjects. The differences associated with vowels suggested formant transitions as important cues for fricative identification. There was no supportable evidence which indicated that a single cue was sufficient for differentiating the voiceless fricatives. The most likely explanation for the performance of the subjects appeared to be a combination of the above parameters.

Further research is indicated to determine the role of the various parameters of low-frequency energy in identifications of voiceless fricatives.

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APPENDIX A

RESULTS OF AUDIOLOGICAL EVALUATION OF SUBJECTS

	SUBJECT				
	AA[a]	RD	RI	LB	LL
1. Thresholds					
a. Pure-tone[b]					
1) 250 cps	5 dB	5 dB	10 dB	10 dB	5 dB
2) 500 cps	10 dB	5 dB	5 dB	10 dB	0 dB
3) 1000 cps	5 dB	20 dB	10 dB	10 dB	5 dB
4) 1500 cps	20 dB	70 dB	30 dB	40 dB	25 dB
5) 2000 cps	50 dB	70 dB	65 dB	70 dB	60 dB
6) 3000 cps	75 dB	100 dB	75 dB	105 dB	80 dB
7) 4000 cps	75 dB	100 dB	70 dB	100 dB	80 dB
8) 6000 cps	75 dB	90 dB	70 dB	NR	75 dB
9) 8000 cps	70 dB	75 dB	55 dB	NR	75 dB
b. SRT	12 dB	22 dB	14 dB	16 dB	6 dB
2. Speech Discrimination (Tape recorded PB-50 lists)					
a. Quiet	84 %	74 %	82 %	72 %	76 %
b. Noise (S/N=+10 dB)	72 %	72 %	78 %	64 %	66 %
3. SISI Scores					
a. 500 cps	0 %	0 %	0 %	0 %	0 %
b. 1000 cps	0 %	20 %	0 %	0 %	0 %
c. 2000 cps	100 %	100 %	95 %	100 %	100 %
4. Comfort level for speech	44 dB	60 dB	44 dB	48 dB	46 dB

[a]Only Subject AA had left ear used as the test ear.

[b]Thresholds re: ISO 1964 Standard. Bone conduction thresholds were within 5 dB of air conducted thresholds for all frequencies for which there was adequate intensity available to test bone conduction.

APPENDIX B

ANSWER FORM FOR THE MAIN EXPERIMENT

(Directions to subjects were to write each syllable as it was presented. They were told to guess if necessary and to give an answer for every syllable presentation.)

Column 1.	Column 2.	Column 3.
1. ________	21. ________	41. ________
2. ________	22. ________	42. ________
3. ________	23. ________	43. ________
4. ________	24. ________	44. ________
5. ________	25. ________	45. ________
6. ________	26. ________	46. ________
7. ________	27. ________	47. ________
8. ________	28. ________	48. ________
9. ________	29. ________	49. ________
10. ________	30. ________	50. ________
		(TURN PAGE)
11. ________	31. ________	
12. ________	32. ________	
13. ________	33. ________	
14. ________	34. ________	
15. ________	35. ________	
16. ________	36. ________	
17. ________	37. ________	
18. ________	38. ________	
19. ________	39. ________	
20. ________	40. ________	

APPENDIX C

ANSWER FORM FOR THE FORCED-CHOICE TASK

(Subjects were told that a pair of syllables would be presented for each trial. One, and only one, syllable would start with the sound given in the sound key. They were to decide if the first or second syllable contained the sound and to circle the corresponding number under Answer Choice. They were told to circle a number for each trial even if they had to guess.)

Trial	Sound Key	Answer Choice		Trial	Sound Key	Answer Choice	
1.	s[a]	1	2	21.	th	1	2
2.	sh	1	2	22.	s	1	2
3.	f	1	2	23.	f	1	2
4.	f	1	2	24.	f	1	2
5.	th	1	2	25.	f	1	2
6.	sh	1	2	26.	f	1	2
7.	f	1	2	27.	th	1	2
8.	f	1	2	28.	sh	1	2
9.	f	1	2	29.	f	1	2
10.	f	1	2	30.	sh	1	2
11.	f	1	2	31.	f	1	2
12.	f	1	2	32.	f	1	2
13.	sh	1	2	33.	f	1	2
14.	sh	1	2	34.	th	1	2
15.	th	1	2	35.	sh	1	2
16.	f	1	2	36.	f	1	2
17.	f	1	2	37.	f	1	2
18.	sh	1	2	38.	s	1	2
19.	sh	1	2	39.	f	1	2
20.	s	1	2	40.	sh	1	2

[a]These are samples of the orthographic symbols given in the test situation.

APPENDIX D

Confusion matrices for syllable identifications by Subject AA. Cell entries from top to bottom represent responses in test sessions one to five respectively.

		RESPONSE															
		/i/				/e/				/o/				/u/			
STIMULUS	Session	/ʃ/	/s/	/f/	/θ/	/ʃ/	/s/	/f/	/θ/	/ʃ/	/s/	/f/	/θ/	/ʃ/	/s/	/f/	/θ/
/ʃ/	1	47	2		1	49	1			48	2			48	1	1	
	2	48	2			49	1			50				50			
	3	48	2			50				50				50			
	4	50				50				50				50			
	5	50				49	1			50				50			
/s/	1		45	2	3	1	46	2	1		50				47	2	1
	2	2	48				44	6			50				50		
	3		50				40	10			50				49		1
	4	3	45	2			48	2			50				50		
	5	5	43	2			48	2			50				49	1	
/f/	1		25	11	14		2	45	3		1	49				47	3
	2		39	8	3		4	46				50				50	
	3		33	14	3		1	49				50				50	
	4		20	28	2			50				50				50	
	5	1	24	22	3		1	49				50				50	
/θ/	1		30	1	19		11	32	7		43	3	4		9	7	34
	2		42	3	5		2	47	1		31	1	18		34		16
	3		9	3	38			50			38		12		2		48
	4		5	18	27			48	2		24	4	22		2		48
	5		4	22	24			50			34	6	10		4		46

APPENDIX D--Continued

Confusion matrices for syllable identifications by Subject RD. Cell entries from top to bottom represent responses in test sessions one to five respectively.

		RESPONSE															
		/i/				/e/				/o/				/u/			
STIMULUS	Session	/∫/	/s/	/f/	/θ/	/∫/	/s/	/f/	/θ/	/∫/	/s/	/f/	/θ/	/∫/	/s/	/f/	/θ/
/∫/	1	39	9	2		3	46		1	40	9		1	45	3		2
	2	40	7	3		15	31	3	1	45	5			48	2		
	3	42	4	4		19	28	2	1	42	8			47	3		
	4	47	3			14	34	1	1	38	12			50			
	5	48	2			14	34	2		46	4			50			
/s/	1	18	32				43		7	6	41	1	2	15	32	2	1
	2	33	16	1		16	22	11	1	2	45		3	9	41		
	3	24	24	1	1	17	24	6	3	1	46		3	11	39		
	4	30	19		1	16	26	2	6	2	46		2	9	41		
	5	30	19	1		23	23	2	2		50			10	40		
/f/	1	2	26	11	11	1	22	4	23		1	44	5			46	4
	2	3	30	11	6	5	3	28	14			48	2	1		47	2
	3	10	14	17	9	1	7	29	13			41	9			48	2
	4	2	13	17	18	5	4	25	16			40	10			48	2
	5	5	14	21	10	1	1	36	12			47	3			50	
/θ/	1		15	6	29	1			49			1	49		3		47
	2		3	9	38	2		9	39		1	1	48		4		46
	3	1	2	11	36	2		10	38			3	47		1		49
	4		2	15	33	1		7	42				50				50
	5		2	19	29	1		13	36		1	1	48		3		47

APPENDIX D--Continued

Confusion matrices for syllable identifications by Subject RI. Cell entries from top to bottom represent responses in test sessions one to five respectively.

RESPONSE

STIMULUS	Session	/i/ /ʃ/	/i/ /s/	/i/ /f/	/i/ /θ/	/e/ /ʃ/	/e/ /s/	/e/ /f/	/e/ /θ/	/o/ /ʃ/	/o/ /s/	/o/ /f/	/o/ /θ/	/u/ /ʃ/	/u/ /s/	/u/ /f/	/u/ /θ/
/ʃ/	1	10	25	14	1	28	21	1		50				37	11		2
	2	5	29	16		21	26		3	50				44	6		
	3	31	10	9		40	8		2	50				48	2		
	4	37	8	5		41	9			50				44	6		
	5	43	2	5		46	4			50				48	2		
/s/	1	4	38	6	2	3	33	5	9	1	47	1	1	11	37	1	1
	2	1	46	3		5	32	7	6	1	49			1	49		
	3	3	45	2		4	42	2	2		49		1	1	49		
	4	2	47	1			45	4	1		50			2	48		
	5	1	49				46	2	2		50				50		
/f/	1	1	8	28	13	3		10	37			50				50	
	2	3	10	26	11		3	31	16			49	1			50	
	3	5	2	23	20			24	26			50				50	
	4	1	3	36	10			26	24			50				50	
	5		2	33	15			33	17			50				50	
/θ/	1		2	15	33	1	1	7	41			1	49		1	1	48
	2			11	39			7	43				50				50
	3			7	43			5	45				50		1		49
	4			3	47			7	43		1		49				50
	5			2	48			3	47		1		49				50

APPENDIX D--Continued

Confusion matrices for syllable identifications by Subject LB.
Cell entries from top to bottom represent responses
in test sessions one to five respectively.

		RESPONSE															
		/i/				/e/				/o/				/u/			
STIMULUS	Session	/ʃ/	/s/	/f/	/θ/	/ʃ/	/s/	/f/	/θ/	/ʃ/	/s/	/f/	/θ/	/ʃ/	/s/	/f/	/θ/
/ʃ/	1	34	14	1	1	45	3	1	1	49	1			49		1	
	2	29	18		3	49	1			49			1	50			
	3	40	9		1	45	4		1	50				49	1		
	4	42	7		1	43	7			50				50			
	5	44	5		1	40	8		2	50				50			
/s/	1	13	34		3	14	27	3	6	2	46	1	1	4	46		
	2	19	30	1		1	44	3	2		50				50		
	3	6	39	1	4	5	42	1	2		47		3		49		1
	4	9	35	1	5	3	44	1	2		48		2		50		
	5	7	38		5	2	46		2	2	43		5		49		1
/f/	1		29	16	5	1	5	26	18			50				50	
	2	4	12	22	12		1	39	10			50				50	
	3	3	14	16	17		1	41	8			50				50	
	4		18	12	20			46	4			50				50	
	5	3	13	18	16			44	6			50				50	
/θ/	1	1	1	8	40		2	16	32		2	7	41		4		46
	2	1	3	12	34			29	21			2	48		4		46
	3	1	3	3	43			23	27		1	4	45		3		47
	4		2	2	46			18	32			3	47		2		48
	5	3	3	5	39			14	36		2	2	46		4		46

APPENDIX D--Continued

Confusion matrices for syllable identifications by Subject LL.
Cell entries from top to bottom represent responses
in test sessions one to five respectively.

		RESPONSE															
		/i/				/e/				/o/				/u/			
STIMULUS	Session	/ʃ/	/s/	/f/	/θ/	/ʃ/	/s/	/f/	/θ/	/ʃ/	/s/	/f/	/θ/	/ʃ/	/s/	/f/	/θ/
/ʃ/	1	40	9		1	34	16			50				47	3		
	2	50				40	10			50				48	1	1	
	3	50				39	11			50				50			
	4	50				49	1			50				50			
	5	50				48	2			50				50			
/s/	1	26	24				50				50			11	39		
	2	39	11				49	1			50			13	37		
	3	45	5			1	49				49		1	2	47		1
	4	45	5			4	40	6			50			4	46		
	5	50				4	45	1		1	48		1		50		
/f/	1	14	31	5			4	46				50				50	
	2	20	9	21				50				50				50	
	3	29	8	8	5		4	46				50				50	
	4	20	2	6	22		1	49				50				50	
	5	24	6	2	18			50				50				50	
/θ/	1	9	31	2	8		5	41	4	4	3		43		18		32
	2	12	10	25	3			50					50		8		42
	3	9	2	1	38			48	2				50		1		49
	4	1	1	2	46			49	1				50		1		49
	5	4			46			50					50				50

APPENDIX E

ACOUSTICAL ANALYSIS OF SYLLABLES

Syllable	Lowest Major Resonance of Fricative[a]	Fricative to Vowel Ratio (Peak to Peak)[b]	Duration of the Syllable[a&b]
/ʃi/	2000 cps	- 9 dB	800 msec
/ʃe/	2000 cps	-15 dB	800 msec
/ʃo/	2000 cps	-14 dB	800 msec
/ʃu/	2000 cps	-10 dB	800 msec
/si/	3000 cps	-10 dB	650 msec
/se/	3000 cps	-13 dB	650 msec
/so/	3000 cps	-16 dB	750 msec
/su/	3000 cps	-18 dB	700 msec
/fi/	--[c]	-28 dB	750 msec
/fe/	--[c]	-27 dB	800 msec
/fo/	--[c]	-25 dB	725 msec
/fu/	--[c]	-32 dB	675 msec
/θi/	--[c]	-22 dB	750 msec
/θe/	--[c]	-24 dB	750 msec
/θo/	--[c]	-22 dB	700 msec
/θu/	--[c]	-23 dB	700 msec

	Second Formant		Third Formant	
Syllable	Onset[a]	Termination[a]	Onset[a]	Termination[a]
/ʃi/	1900 cps	2125 cps	2375 cps	2500 cps
/ʃe/	1600 cps	2000 cps	2125 cps	2375 cps
/ʃo/	1625 cps	875 cps	2125 cps	2375 cps
/ʃu/	1625 cps	1000 cps	2125 cps	2250 cps
/si/	1690 cps	2125 cps	2375 cps	2625 cps
/se/	1500 cps	2000 cps	2375 cps	2400 cps
/so/	1250 cps	875 cps	2375 cps	2250 cps
/su/	1500 cps	875 cps	2250 cps	2125 cps

APPENDIX E--CONTINUED

	Second Formant		Third Formant	
Syllable	Onset[a]	Termination[a]	Onset[a]	Termination[a]
/fi/	1750 cps	2000 cps	2250 cps	2600 cps
/fe/	1400 cps	1875 cps	2125 cps	2375 cps
/fo/	900 cps	750 cps	2125 cps	2125 cps
/fu/	1000 cps	875 cps	2125 cps	2125 cps
/θi/	1750 cps	2125 cps	2375 cps	2500 cps
/θe/	1250 cps	1750 cps	2250 cps	2250 cps
/θo/	1250 cps	800 cps	2125 cps	2000 cps
/θu/	1250 cps	800 cps	2125 cps	2125 cps

[a]Derived from spectrographic analysis

[b]Derived from level recorder tracings. Recorder was calibrated to 1 mv= 0 dB.

[c]No demonstrated major resonance. With the input system overloaded the spectrum was nearly continuous throughout the frequency range of the spectrograms.

APPENDIX F

SUMMARY OF ANALYSIS OF VARIANCE FOR ALL RESPONES BY SUBJECT AA. N=4000.

Source of Variance	df	Mean Square	F
Sessions	4	307.82[a]	4.82[b]
Syllables	15	3273.31	51.28[b]
Fricatives	3	10,077.82	7.26[b]
Vowels	3	2162.04	1.57
F x V	9	1375.56	
Residual	60	63.83	
Total	79		

[a]Data transformed to angles corresponding to percentages. Angle=Arcsin $\sqrt{\text{Percentage}}$.

[b]Significant at the .01 level.

NEWMAN-KEULS SEQUENTAL RANGE TEST FOR DATA OF SUBJECT AA.

Session	$\bar{x}$	$\bar{x} - \bar{x}_1$	$\bar{x} - \bar{x}_2$	$\bar{x} - \bar{x}_5$	$\bar{x} - \bar{x}_3$
4	74.20	10.65[a]	8.98[a]	4.32	3.20
3	71.00	7.45[a]	5.78	1.12	
5	69.88	6.33	4.66		
2	65.22	1.67			
1	63.55				

[a]Significant at .05 level.

APPENDIX F--Continued

SUMMARY OF ANALYSIS OF VARIANCE FOR ALL RESPONSES BY SUBJECT RD. N=4000.

Source of Variance	df	Mean Square	F
Sessions	4	103.02[a]	1.58
Syllables	15	1496.99	22.99[b]
Fricatives	3	813.28	1.16
Vowels	3	4563.83	6.49[b]
F x V	9	702.62	
Residual	60	65.11	
Total	79		

[a]Data transformed to angles corresponding to percentages. Angle=Arcsin $\sqrt{\text{Percentage}}$.

[b]Significant at the .01 level.

APPENDIX F--Continued

SUMMARY OF ANALYSIS OF VARIANCE FOR ALL RESPONSES BY SUBJECT RI. N=4000.

Source of Variance	df	Mean Square	F
Sessions	4	597.42[a]	8.88[b]
Syllables	15	1174.61	17.47[b]
Fricatives	3	550.56	1.66
Vowels	3	4329.67	13.08[b]
F x V	9	330.94	
Residual	60	67.24	
Total	79		

[a]Data transformed to angles corresponding to percentages. Angle=Arcsin $\sqrt{\text{Percentage}}$.

[b]Significant at the .01 level.

NEWMAN-KEULS SEQUENTAL RANGE TEST FOR DATA OF SUBJECT RI.

Session	$\bar{\bar{x}}$	$\bar{\bar{x}} - \bar{\bar{x}}_1$	$\bar{\bar{x}} - \bar{\bar{x}}_2$	$\bar{\bar{x}} - \bar{\bar{x}}_3$	$\bar{\bar{x}} - \bar{\bar{x}}_4$
5	78.76	15.70[a]	10.70[a]	6.04	3.78
4	74.98	11.92[a]	6.92	2.26	
3	72.72	9.66[a]	4.66		
2	68.06	5.00			
1	63.06				

[a]Significant at .05 level.

APPENDIX F--Continued

SUMMARY OF ANALYSIS OF VARIANCE FOR ALL RESPONSES BY SUBJECT LB. N=4000.

Source of Variance	df	Mean Square	F
Sessions	4	121.61[a]	3.46
Syllables	15	1183.90	33.72[b]
Fricatives	3	393.41	1.00
Vowels	3	4142.81	8.98[b]
F x V	9	461.10	
Residual	60	35.11	
Total	79		

[a]Data transformed to angles corresponding to percentages. Angle=Arcsin $\sqrt{\text{Percentage}}$.

[b]Significant at the .01 level.

APPENDIX F--Continued

SUMMARY OF ANALYSIS OF VARIANCE FOR ALL RESPONSES BY SUBJECT LL. N=4000.

Source of Variance	df	Mean Square	F
Sessions	4	180.90[a]	1.34
Syllables	15	3742.60	27.63[b]
Fricatives	3	2728.54	1.01
Vowels	3	7893.00	2.92
F x V	9	2697.14	
Residual	60	135.45	
Total	79		

[a]Data transformed to angles corresponding to percentages. Angle=Arcsin $\sqrt{\text{Percentage}}$.

[b]Significant at the .01 level.

APPENDIX G

RESPONSES TO THE FORCED-CHOICE TASK (Experiment II)

(The left hand member of each syllable pair contained the fricative to be identified. N=50 per pair. Responses from the last test session of the main study--experiment I-- are given for comparison.)

Subject	Experiment	Syllable Pairs[a] /si-ʃi/	/ʃi-si/	/fi-si/	/fi-θi/	/fi-ʃi/
AA	I	43- 5	50- 0	22-24	22- 3	22- 1
	II	50- 0	48- 2	49- 1	23-27	50- 0
RD	I	19-30	48- 2	21-14	21-10	21- 5
	II	49- 1	38-12	30-20	30-20	42- 8
RI	I	49- 1	43- 2	33- 2	33-15	33- 0[b]
	II	44- 6	49- 1	48- 2	46- 4	47- 3
LB	I	38- 7	44- 5	18-13	18-16	18- 3
	II	42- 8	45- 5	48- 2	43- 7	47- 3
LL	I	0-50	50- 0	2- 6	2-18	2-24
	II	26-24	28-22	45- 5	23-27	50- 0

		/fe-θe/	/θe-fe/	/ʃe-se/	/se-ʃe/	/su-ʃu/
AA	I	40- 0	0-50			
	II	23-27	19-31			
RD	I	36-12	36-13	14-34	23-23	40-10
	II	42- 8	37-13	28-22	28-22	50- 0
RI	I	33-17	47- 3	46- 4		
	II	46- 4	43- 7	49- 1		
LB	I	44- 6	36-14	40- 8		
	II	40-10	36-14	48- 2		
LL	I	50- 0	0-50	48- 2		
	II	29-21	23-27	40-10		

APPENDIX G--Continued

Subject	Experiment	Syllable Pairs[a] /θi-fi/	/θi-si/	/θo-so/	/fo-θo/	/ʃo-so/
AA	I	24-22	24- 4	10-34		
	II	29-21	49- 1	47- 3		
RD	I	29-19	29- 2	48- 1	47- 3	46- 4
	II	29-21	50- 0	50- 0	50- 0	49- 1

[a]The left hand syllable of each pair was the stimulus in experiment I.

[b]Subject RI was given the sh cue for /fi-ʃi/.

VITA

of

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EXAMINATION AND THESIS REPORT

Candidate: Donald Leroy Lawrence

Major Field: Speech

Title of Thesis: Investigation of Identification of Voiceless Fricative-Vowel Syllables by Subjects with High-Frequency Hearing Impairment.

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July 13, 1967