Effects of vocalic formant transitions and vowel quality on the English [s]–[š] boundary

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The effects of the vocalic portion of fricative–vowel syllables on the perception of alveolar and palatal fricatives were examined. The fricative noises were synthesized to represent a continuum from [s] to [š]; the vowels ranged from [u] to [i] through [ɪ̈] and [ü]. The vocalic formant transitions were of two types, those appropriate to [s] and those to [š]. All stimuli were presented in forced-choice labeling tests. The boundary between [s] and [š] for English-speaking listeners was found to vary as a function both of transitions and of vowel. The effect of the transitions was clear and straightforward: An ambiguous fricative noise was heard more often as [s] before [s] transitions, and as [š] before [š] transitions. The quality of the vowel clearly had an effect, but the interpretation of the effect in terms of the perception of coarticulation was not clear. The responses of listeners who were unfamiliar with languages which use [ü] and/or [ɪ̈] distinctively were not significantly different from those of listeners who were familiar with such languages.

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INTRODUCTION

Although an obvious cue for the place of articulation of fricatives lies in the spectrum of the frication noise, other cues are identifiable. One such cue is provided by the formant transitions of the following vocalic segment, whose effect was demonstrated in a preliminary way by Harris (1958). In that experiment, natural speech syllables composed of English fricatives followed by various vowels were copied onto magnetic tape and cut into fricative and vocalic segments which were then recombined so that each noise occurred with each vocalic portion (including the transitions appropriate for each of the places of articulation). Transitions were found to determine the perceived place of articulation for the dental and labial fricatives [f, θ, v, ð], but the alveolar and palatal noises [s, š, z, ž] seemed strong enough cues to outweigh any cues contained in the transitions. This result has been replicated (LaRiviere, Winitz, and Herriman, 1975); however, McCasland (1978) recently reported that, for fricatives in intervocalic position, transition cues may occasionally override the cues provided by the [s] and the [š] noise. Since the natural noise, at least in utterance initial position, is such a powerful cue, tape-splicing experiments are inherently insensitive to possible effects on perception due to the alveolar and palatal transitions. Such effects were in fact found by Delattre, Liberman, and Cooper (1964) for the voiced fricatives [z] and [ž] when, in synthetic speech, a neutral noise was used before varying transitions. The present experiments were designed in part to provide a method sensitive enough to determine whether the transitions affect the perception of the voiceless alveolar and palatal fricatives as well.

Another goal of the present study was to see whether the perception of a fricative would be affected by the quality of a following vowel. Such differences in perception were found for speakers of Japanese in experiments by Kunisaki and Fujisaki (1977). The boundary between [s] and [š], measured on a synthetic noise continuum, shifted when the fricative noises were followed by different vowels. (The nature of a preceding vowel was found to have a much smaller effect on the boundary.) Their results for the vowels [a, e, o, u] suggested that the important feature of the vowel was rounding. An ambiguous noise was more likely to be heard as [š] when it preceded one of the unrounded vowels [a, e] than when it preceded one of the rounded ones [u, o]. (In Japanese, [s] does not occur before [i].) Since, in articulation, lip rounding in anticipation of the rounded vowels would lower the frequency of a preceding fricative noise, this result suggests "that the influence of context in speech production is corrected in speech perception" (Kunisaki and Fujisaki, 1977, p. 91). The present experiments were intended to replicate these findings with a somewhat different set of vowels.

The final purpose of the present experiments was to determine whether subjects whose native language does not use certain vowels distinctively would nevertheless show a unique effect of each such vowel on the perception of a preceding fricative. This was tested by using vowels which do not occur phonemically in English, as well as English vowels.

I. EXPERIMENT 1

To determine the boundary between [s] and [š], a fricative noise continuum was needed. Synthetic noises could be systematically varied and were therefore used. However, the vocalic segments needed to vary only by vowel quality and by transitions. Since natural speech controls the transitions automatically in the [s] and [š] environments, and since vowel quality can be controlled to some extent by training, natural-speech vocalic segments were used.

A. Method

A male linguist familiar with languages using the four vowels [i, u, ɪ̈, ü] pronounced a set of eight syllables combining each of the vowels with initial [s] and [š]. These utterances were recorded on magnetic tape and were then digitized using the Haskins Laboratories

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pulse code modulation (PCM) system. The fricative noises were cut off (at the first pitch pulse) with the aid of magnified waveform displays, and the resulting eight vocalic segments were then combined with the noises of a ten-member fricative continuum produced on the OVEIIIc synthesizer at Haskins Laboratories. The synthetic fricatives were 150 ms in length and differed in the frequencies of the two fricative formants, which increased in approximately equal steps from the lower, more [š]-like noises to the higher, more [s]-like noises (see Table I). The bandwidths varied from approximately 100 Hz for the lowest frequency to approximately 800 Hz for the highest. There was no antiformant (KO on the synthesizer was 0). The amplitude rose gradually for the first 70 ms, remained at a constant level for 50 ms, then declined to half the maximum amplitude during the last 30 ms. The amplitudes of all members of the continuum were adjusted to be roughly equal. The maximum amplitude of the fricative noise was an average of 10.3 dB lower than that of the vowel.

The acoustic characteristics of the eight vocalic segments are presented in Table II. None of the $F1$s had noticeable transitions. The measurements of the transitions' duration include only the steep portion of formant change; some more gradual changes occurred after these transitions in some of the vowels. In [u], the transition is equal in duration to the entire vocalic segment. While this quality gives an American English [u], it makes problematic some of the comparisons based on vowel quality. Rounding may not have been constant throughout the vowel, thus allowing higher frequencies in the preceding natural fricatives, and complementary effects in perception. The amplitude of the vocalic segments was fairly constant after the initial rise (~25 ms) up to the decline (~75 ms from the end). All syllables had a falling intonation.

The ten fricatives were combined with the eight vocalic segments (four vowels, each with [s] or [š] transitions). The resulting 80 stimuli were presented in randomized order, six repetitions per session, two sessions per subject. The subjects were five Yale students who were native speakers of English and who were unfamiliar with languages containing the foreign vowels [ï] and [ü]. The subjects were asked only to identify the fricative as "s" or "sh". Stimuli were presented binaurally over Telephonics TDH-39 earphones at the rate of one every three seconds.

In order to check that the two foreign vowels were in fact identified as either [i] or [u] and not some other English vowel, a vowel identification test was conducted at the end of the last session. The eight experimental utterances, including the original frication, were presented together with ten more syllables, [s] and [š] before [e, ö, o, ë, a], all produced by the same talker. Five repetitions of each stimulus were presented in randomized order. In order to avoid using special symbols which would necessitate training the subjects, ten English words were chosen for the response sheets. The words were: see/she, say/Shea, saw/Shaw, so/show, sue/shoe. The results of the identification test were quite consistent. [i] and [u] were always heard correctly, and [ü] was heard as [i] and [ï] as [u] over 95% of the time. Although discriminability was not tested for, the subjects reported informally that they heard more than one vowel per English category.

TABLE II. Acoustic properties of vocalic segments, experiment 1. Formant values are in Hz; durations are in ms.

Duration of vocalic segment	$F1$	$F2$ origin, duration of transition, $F2$ endpoint	$F3$ origin, duration of transition, $F3$ endpoint
[(s)u] 300	250	1600, 300, 850	2750, 130, 2100
[(š)u] 300	300	1800, 300, 850	2100, (0), 2100
[(s)i] 400	250	1150, 60, 1000	2450, (0), 2450
[(š)i] 300	250	1550, 60, 1000	2150, 130, 2450
[(s)ü] 400	250	1650, 130, 1950	2300, (0), 2300
[(š)ü] 350	250	1950, (0), 1950	2150, (0), 2150
[(s)ï] 500	250	1700, 130, 2300	2500, 130, 3000
[(š)ï] 500	250	2100, 130, 2300	2750, 130, 2900

B. Results

When the results for the test were tabulated, it became clear that the subjects were not perceiving the first five stimuli of the continuum reliably either as [s] or [š]. While there was a bias in the response toward whichever fricative was appropriate to the transition which was present, many of the data points were at or near chance. Presumably, this occurred because the frequencies of these noises were too low to give an acceptable [š]. A perceptual test of the fricative noise alone confirms this (see Table III). (Six subjects made ten judgements per stimulus. The results indicate that the lowest noises were inappropriate, and the near randomness of the responses to the lower end of the scale in experiment 1 reflected that.) Therefore, the results from the first five stimuli will be omitted for clarity of presentation.

In Fig. 1, the average percentage of "sh" responses is plotted against the frequency of the first fricative formant. For each of the four vowels, the responses for the [s]-transition stimuli are presented separately from those for [š]-transition stimuli. One can see that in each case, there were far fewer "sh" responses when the transition was appropriate to [s] than when it

TABLE I. Fricative formants for experiment 1, in Hz.

	Stimulus number									
	1	2	3	4	5	6	7	8	9	10
$F2$	3020	3488	4030	4655	5226	5699	6397	6778	7391	8061
$F1$	1008	1307	1646	2074	2328	2613	3019	3293	3591	4032

TABLE III. Identification of isolated fricative noises, experiment 1.

	Stimulus number									
	1	2	3	4	5	6	7	8	9	10
% "sh" response	75	69	96	90	98	97	83	37	22	8

was appropriate to [š]. The most extreme case is that of [ï] with [s] transitions, for which "sh" responses never got above 28%. It is unclear why this particular vowel/transition combination should be such an overriding cue. The shapes of the response functions in Fig. 1 also suggest that stimulus 6 (with a first formant frequency of 2613 Hz) was actually the best [š] noise, since it was most effective in competing against the conflicting [s] transitions. (Stimuli 1–5 all had lower percentages of "sh" responses.)

Although it is clear from Fig. 1 that the four vowels differed in their effects on fricative perception, these effects are difficult to compare. In Fig. 2, the same data has been replotted, but with the results for [s] transitions in Fig. 2(a), and those for [š] transitions in Fig. 2(b). The effect of the vowel is now apparent in the varying points at which the responses are evenly divided between "s" and "sh" (which point will be defined as the s/š boundary). With [š] transitions, the effect of the vowel can be as large as 500 Hz, and it would probably have been similarly large for the [s] transitions if the response had approached 100% for all the vowels, or even if the response for [ï] had reached 50% at all. For each transition, the percentage of "sh" responses was much less for [ï] than for the other three vowels. This was surprising since [ï], being acoustically intermediate between [i] and [u], was expected to have a corresponding intermediate effect on the perception of the fricatives. Since Kunisaki and Fujisaki (1977) hypothesized that a rounded vowel would give a lower s/š boundary, and since [u] and [ï] differ in just that feature of rounding, we would predict that [u] would have the lower boundary. The above-mentioned glide effect in the [u] may be responsible for this discrepancy.

Analysis of variance was performed on the total number of "sh" responses, since not all vowels had boundaries. The effect of the transitions was significant $F(1,4)=23.2, p<0.01$, as was that of the vowel $F(3,12)$

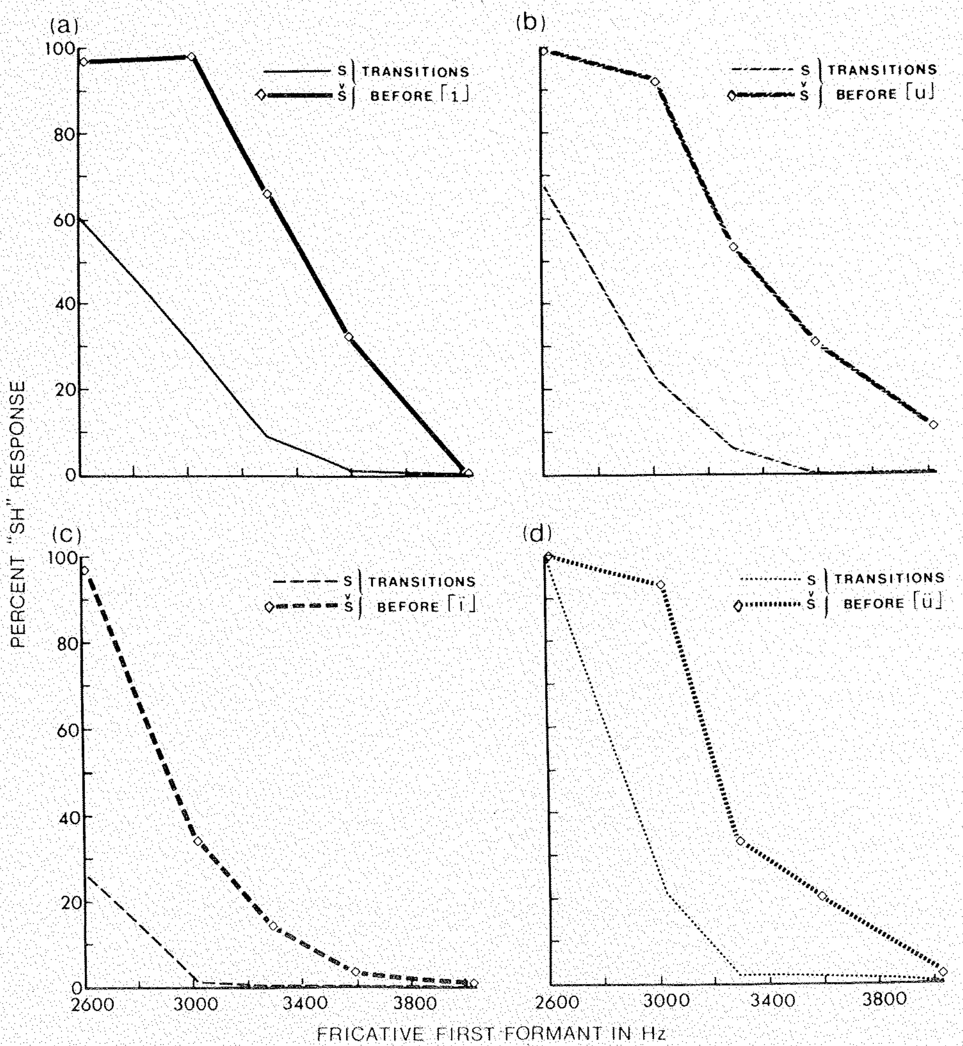

FIG. 1. Effect of the differing ([s] or [š]) transitions on the perception of the synthetic fricatives, plotted separately for each vowel. (Experiment 1.)

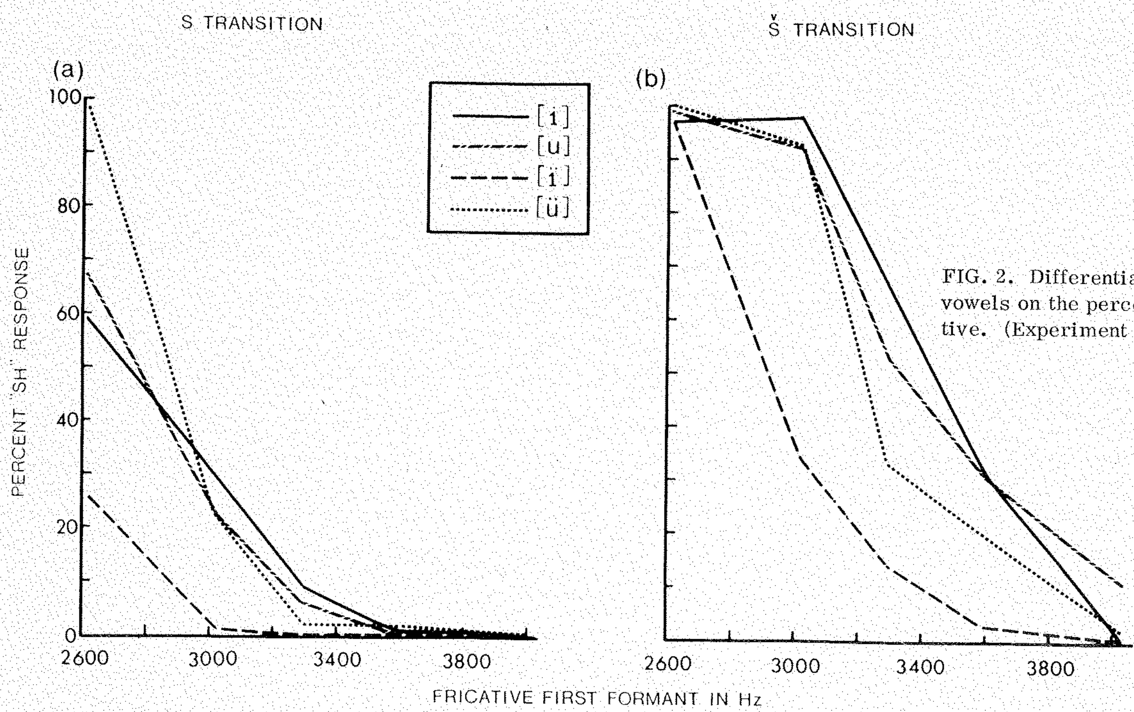

FIG. 2. Differential effects of the four vowels on the perception of the fricative. (Experiment 1.)

$=17.4$, $p<0.001$. In addition, there was a significant interaction between vowel and transition effects $F(3,12)=3.7$, $p<0.05$ due to the large transition effect of [ï].

II. EXPERIMENT 2

While the transitions have a clear effect in experiment 1, the lack of an s/š boundary for [ï] makes comparative measurements of the transitions' effects impossible. Clear cases of "sh" for all vocalic segments would make numerical comparison meaningful. Also, while there was definitely an effect of the vowel on the perception of the fricative, the results are difficult to interpret. Since experiment 1 used only one token of each vocalic segment, there is a good possibility that the vowel effects reflected token-specific peculiarities. So, in the second experiment, synthetic vocalic segments were used as well as synthetic fricatives; thus vowel quality could be controlled for and systematically varied. In order to facilitate comparison of the two experiments, the same high vowel range ([u]) to [i]) was used.

A. Method

Again using the Haskins OVEIIIc synthesizer, a vowel continuum of eight stimuli was produced, with F1 held constant at 250 Hz, and F2 and F3 systematically varied (see Table IV). These vowels were perceived by the experimenter as ranging from [u] to [i], going through [ï] and [ü], with two stimuli in each vowel category. Three expert phoneticians were asked to judge the vowel quality of the stimuli. The endpoints were reliably classed as [u] (sometimes [o]) and [i]. The intermediate values were judged as continuous from back to front. One listener agreed with the experimenter in his rounding judgments; of the other two, one was biased toward hearing unrounded vowels, the second toward rounded. The vowel amplitude was steady up to the last 50 ms, and then fell off linearly. The steady amplitude was an average of 12.5 dB more intense than that of the fricative noise. Fundamental frequency rose quickly (40 ms) from 110 to 120 Hz, then fell linearly to a final value of 100 Hz. The fixed F4 and F5 formants added by the OVEIIIc synthesizer were filtered out.

To model the [s] and [š] transitions of the first experiment, two loci for the second formant were postulated (see Delattre *et al.*, 1964). The most divergent loci which would nonetheless still give integrable transitions (i.e., not give rise to a "click" percept, as determined by the experimenter) were chosen for the experiment. A satisfactory locus for [s] was found at 1500 Hz, and for [š] at 2000 Hz. Transitions did not reach their loci, but rather started at a point which would be 10 ms after the beginning if the transition had been 50 ms in duration. In effect, the transitions were 40 ms long, and pointing at, but not reaching, their loci. The first and third formants were left without transitions; the measurements from the first experiment (Table II) indicated that F1 had no transition and that F3 often had none. Leaving F3 transitionless did not noticeably reduce the acceptability of the syllables and had the advantage of reducing the number of variables.

For this experiment, a different fricative continuum was synthesized, again with ten members but covering

TABLE IV. Synthetic vocalic segments, experiment 2, in Hz.

	Stimulus number							
	1	2	3	4	5	6	7	8
$F3$	2000	2104	2197	2295	2396	2502	2594	2709
$F2$	800	1000	1198	1404	1600	1796	2001	2198

TABLE V. Fricative formants for experiment 2, in Hz.

	Stimulus number									
	1	2	3	4	5	6	7	8	9	10
$F2$	2614	2769	3020	3389	3488	3695	3803	3915	4030	4523
$F1$	2015	2197	2466	2690	2769	2850	3019	3108	3199	3489

a somewhat different range (see Table V). The lower end of the scale, it was hoped, would give clear [š] percepts; the upper end was lower than the usual natural values for [s] but still gave acceptable [s] percepts. This range was designed to give the subjects a roughly equal number of "s" and "sh" judgements, and s/š boundaries in midscale. Results from a perceptual test of the friction alone (six subjects, ten repetitions of each friction) indicate that the range was appropriate (see Table VI). The OVEIIIc pole/zero ratio ($K0$) was 12 dB; this value has the effect of suppressing noise below the first pole ($K1$) and thus reducing the chance that this would confuse the subjects, as may have happened in the first experiment. The fricative noises were 150 ms long. Bandwidths varied from approximately 200 Hz for the lowest frequency to approximately 475 Hz for the highest.

The sixteen vowels (eight second formant values, two transitions each) were combined with the fricatives yielding 160 stimuli. These were randomized as before, and presented to subjects for forced choice labeling as "s" or "sh". Three randomizations, each containing two tokens of each stimulus, were presented in each session. The stimulus rate was one every three seconds. Nine Yale undergraduates with varying amounts of linguistic training (see below) were subjects for three sessions each.

B. Results

The results from experiment 2 are presented in Figs. 3, 4, and 5. Figure 3 presents each vowel separately, contrasting the [s] and [š] transitions. Here again, as in experiment 1 (Fig. 1), the [s] transition always drew more [s] responses. Thus the [s]-transition response curve is to the left of the [š]-transition response curve in Figs. 3(a)–3(h). Since the s/š boundary is found at the point where the response function crosses the 50% line, this means that the boundary is at a lower noise frequency when [s] transitions follow than when [š] transitions follow. This replicates the results from experiment 1, although the effect is smaller. However, the effect, as seen in analysis of variance on individual s/š boundaries, was highly significant $F(1,8)=90.9$, $p<0.0001$. Similarly, the effect of the vowel was significant $F(7,56)=28.1, p<0.0001$. There was also an interaction between transition and vowel $F(7,56)=5.5$, $p<0.0001$. As can be seen in Fig. 3 (and even better in Fig. 5), the transition effect diminished somewhat at the [i] end of the vowel continuum.

TABLE VI. Identification of isolated frictive noise, experiment 2.

	Stimulus number									
	1	2	3	4	5	6	7	8	9	10
% "sh" response	100	95	99	77	69	42	39	25	18	11

In Fig. 4, we can see the effect of the vowel on the boundary. Since there are eight vowels instead of four, the graph is rather difficult to read. Nonetheless, we can see that the change effected by the two most extreme vowels is approximately 200 Hz. While this numerical value is less than that from the natural-speech experiment, it, like that previous result, is of the same order of magnitude as the effect due to the transition. The expectation that [u] would give the lowest boundary, [i] the highest, and the other vowels something in between was borne out.

To make the relative effect of each vowel more apparent, the s/š boundaries were determined for each vocalic segment by combining the responses of all subjects and finding the crossover points; these are plotted in Fig. 5. F2 frequency has been chosen as a convenient independent variable, since it was varied systematically. The frequency of the boundary tends to increase as the vowel goes from the [u]-like to the [i]-like. This occurs with both [s] and [š] transitions. The [s]-transition slope has significant linear and quadratic trends $F(8,22)=4, 4.9$, $p<0.01$, while the [š]-transition slope has only a significant linear trend $F(8,22)\,5$, $p<0.01$. A significant higher-order trend would have indicated that the boundaries followed a step function, and thus that vowel category interacted with the vowel effect. As the results stand, though, the possibility that the vowel effect is continuous and independent of category remains open.

The subjects were divided into three groups, based on their familiarity with the foreign speech sounds. The most sophisticated group had had at least a one-semester course in linguistics, which included articulatory phonetics and transcription of foreign sounds. The three subjects in this group had also studied languages containing [ü]; two were fluent in French. Three other subjects, comprising the second group, had studied languages containing either [ü] or [ï], but had had no specific linguistic training. The last group of three had no linguistic training, nor had they ever studied any languages containing the vowels [ï] or [ü]. Analysis of variance in individual s/š boundary values showed no significant difference (at the 0.05 level) among the responses given by these three groups, nor was there any interaction of group with any other variable. For at least these levels of differing linguistic sophistication, familiarity with the foreign vowels did not seem to affect performance.

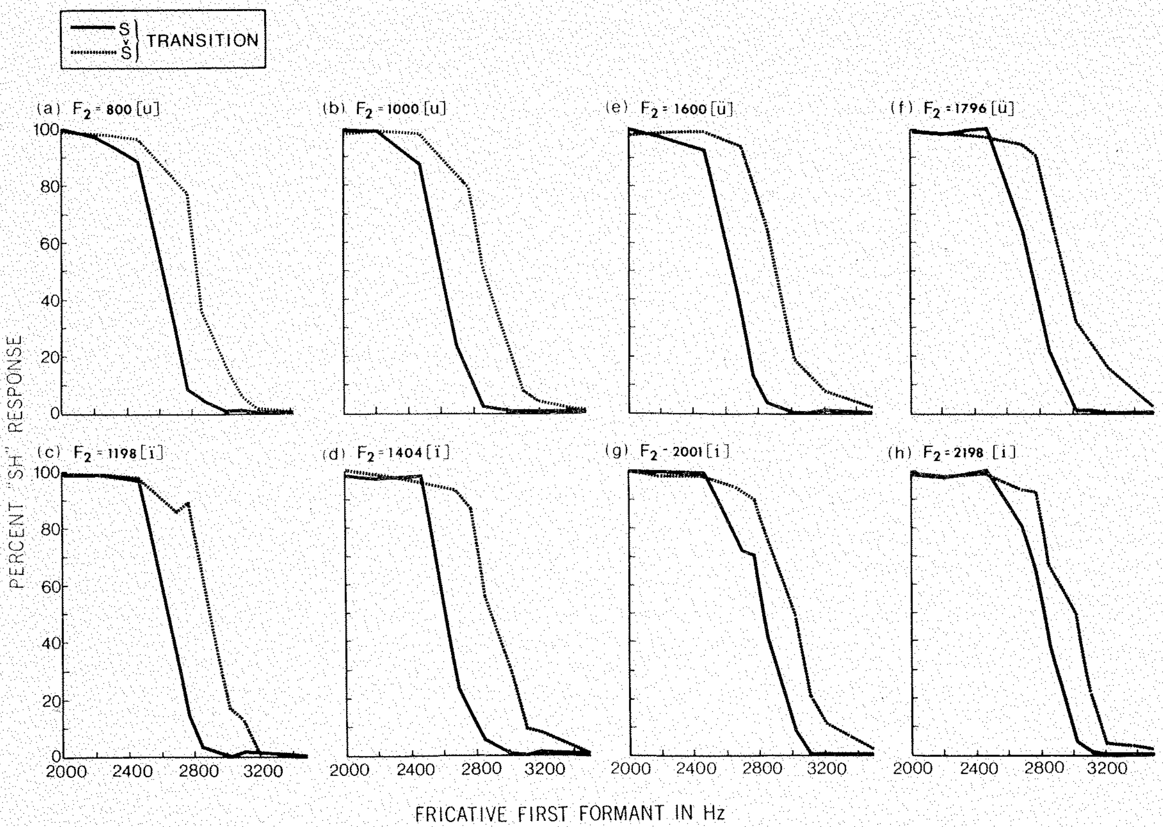

FIG. 3. Effect of synthesized [s] and [š] transitions on the perception of synthesized fricatives. Plotted separately for each of eight vowels, identified both by F2 values and nominal vowel quality. (Experiment 2.)

III. DISCUSSION

In earlier experiments concerning the effect of vocalic formant transitions on the perception of fricatives, the fricative noise was not systematically varied. Thus it was not possible to determine the boundaries between fricatives, nor the amount of shift in the boundaries which is due to the transitions. In the present two experiments, we have seen that holding the vowel constant and changing only the transitions, from those appropri-

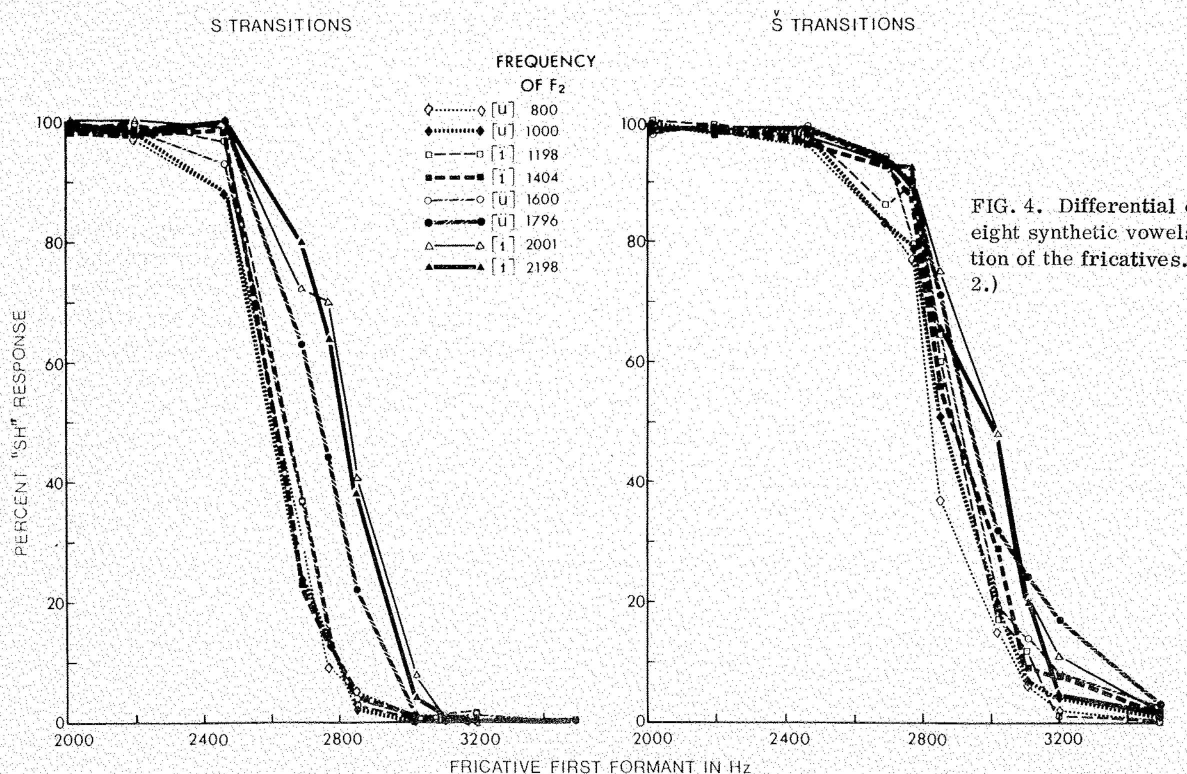

FIG. 4. Differential effects of the eight synthetic vowels on the perception of the fricatives. (Experiment 2.)

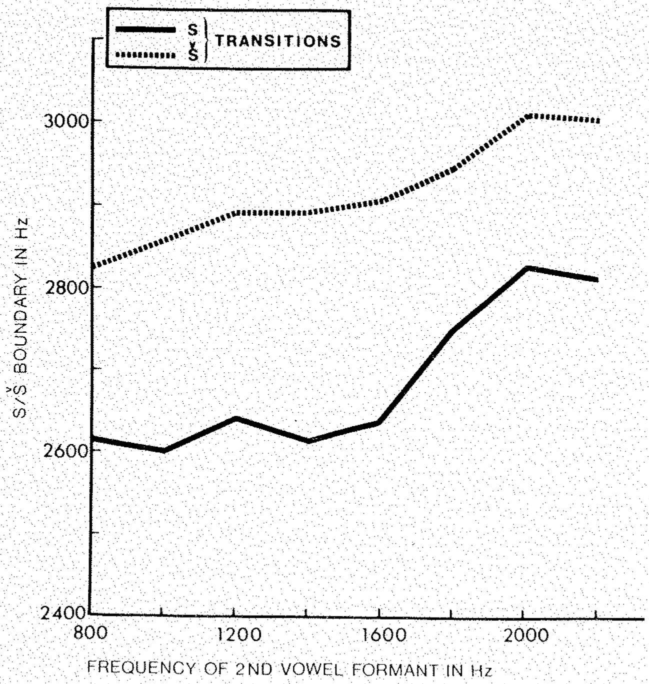

FIG. 5. As determined from Fig. 4, s/š boundaries plotted (arbitrarily) against F2 of the synthesized vowels. The data for the two transitions are presented separately. (Experiment 2.)

ate to [s] to those for [š], can shift the s/š boundary by as much as 200 to 500 Hz in the first fricative formant. In addition, a change in the following (high) vowel produces a shift of around 200 to 500 Hz as well. The larger shifts occurred in experiment 1, where natural speech was combined with synthetic noises. Some possible explanations for this difference in magnitude are presented below.

The contribution of the transitions to the perception of the fricatives may be compared to their corresponding role in the perception of stops. Dorman *et al.* (1977) found that, in some contexts, the transitions had more effect on perception of place of articulation of the stop than the plosive burst; in other contexts, the burst was the deciding cue. Since the burst consists of noise produced at the point of articulation of the consonant, it has a natural analog in the noise of the fricative consonant, which is also produced at the point of articulatory constriction. When the fricative noise is a strong cue, as it is when it has the archetypical frequency values of [s] or [š], the noise is the deciding cue. If the noise is a weaker cue, as with the ambiguous noises, the transitions take on more weight as cues. The fricative noise is a robust signal, and the archetypical fricative noises are easily identifiable in isolation. It is interesting, therefore, that such a long and steady noise should show context effects similar to those of the much more transient stop burst.

The previously mentioned experiment by Kunisaki and Fujisaki (1977), which examined the effect of vowel context on the s/š boundary in Japanese, led to the hypothesis that the effect was due to the presence or absence of rounding. The present results do not directly address the question of whether rounding is the only relevant parameter. Still the explanation that Kunisaki and Fujisaki offer for the effect of rounding does seem to apply, at least to some of the results. Since the second experiment used foreign as well as native vowels, identification tests were not feasible. If, however, the synthetic vowels were perceived by the subjects as the vowels they were intended to reproduce, the results of experiment 2 show the same effect as experiment 1. Since anticipatory rounding in articulation (see Carney and Moll, 1971, Bell-Berti and Harris, 1979) would lower the frequency of sounds being produced, the appearance of a lower s/š boundary for the rounded vowels compared with the unrounded vowels ([u] with [ï] and [ü] with [i]) would indicate that this coarticulation is being compensated for in perception. This holds for the comparison of [u] with [i] also. If we were to take the same approach to the possible effects of the front/back distinction, then we would expect back vowels to have a lower boundary than front vowels. The resonating cavity should be somewhat longer for back vowels (based on the relatively retracted position of the tongue in producing [s] before [u] compared with [i] as seen in Carney and Moll, 1971), and the fricative noise would thus be somewhat lower as well. Thus the combined effect of the two dimensions would lead us to predict that [i] would give a high s/š boundary, [u] a low one, and [ï] and [ü], something in between. This is just what experiment 2 gives us; however, experiment 1 does not give clean enough results to make the comparison. More research is necessary to obtain a definitive explanation of the combined effects of the rounded/unrounded and front/back dimensions.

The transitions used in the second experiment did not exert as much influence on the fricative boundary as the natural transitions of experiment 1. While the parallel decrease in the size of the effect of vowel quality suggests that the vocalic segment as a whole provides a weaker set of cues when it is synthetic, the decrease could also be due to the presence in the natural speech of secondary cues which are not modeled in the synthetic vocalic segments of experiment 2. Although the F3 transitions of the vocalic segments in the first experiment did not seem to vary systematically with the fricative, subsequent manipulation of synthetic syllables by this experimenter showed fairly clearly that changing F3 transitions as well as F2 transitions could affect ambiguous noises more decisively than vocalic segments with only the F2 transition changed. Thus the smaller effect of the transitions in the second experiment may be due to the lack of F3 transitions. In addition, the trajectories of the synthetic transitions were derived from a simple locus theory, which assumed one constant locus for each of the two fricatives. Cinefluorographic studies (Carney and Moll, 1971) show that this might not in fact be the case; the loci might shift before the different vowels. So the stimuli of the second test might not have reproduced as much of the coarticulatory effects as in the first test, which combined synthetic noises with natural transitions (which presumably would show this vowel-specific shift if it is really present).

Finally, there was no significant difference in the performance of the phonetically naive subjects compared to those with some linguistic sophistication and those with a good deal of sophistication. Whatever the effect of the following vowel turns out to be when more data is available, it seems that it is an effect which is shown even by those who do not use certain of the vowels distinctively. Thus it seems that subjects are reacting to the acoustic or narrowly defined phonetic characteristics of the vowels rather than to their perceived (phonemic) category.

In sum, both the nature of the following vowel and its initial formant transitions contribute to the perception of fricative noises. The effect of the transitions is as large as, or larger than, the effect of the vowel. It seems that the vowel effect is insensitive to linguistic experience.

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