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Differences in fricative production between children and adults: Evidence from an acoustic analysis of /ʃ/ and /s/

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(Received 20 January 1987; accepted for publication 11 September 1987)

Speech samples of 12 speakers (8 children and 4 adults) producing the fricatives /s/ and /ʃ/ followed by the vowels /i/ and /u/ were analyzed to locate the major spectral prominences. Results showed that the fricative low-frequency prominences for children's samples differed from those of adults in three important ways: (1) They were generally higher in frequency; (2) they were greater in amplitude relative to higher frequency regions; and (3) they showed greater effects of vowel context. The first finding can be explained by a simple scaling of adult models of fricative production to accommodate children's smaller vocal tracts. The other two findings suggest, however, that there are other anatomical and articulatory differences between children and adults affecting fricative production. The data presented here suggest that one important difference may be the relative sizes of the fricative constriction and the glottal opening.

PACS numbers: 43.70.Bk, 43.70.Ep, 43.72.Ar

INTRODUCTION

Earlier studies showing acoustic and perceptual differences between adults' and children's fricatives raised the question of possible production differences. Nittrouer *et al.* (1988) found that /s/ and /ʃ/ noises of children were spectrally more similar than were those of adults, and that there was greater evidence of anticipatory vowel coarticulation within the fricative portion of the signal for children. On examining /s/ spectra only, Weismer *et al.* (1980) identified a trend similar to the first by reporting these spectra to differ in shape for children and adults. This spectral difference may have resulted from the children producing /s/ noises with spectral shapes more closely resembling those of /ʃ/, although this cannot be determined from their study. Another study (Nittrouer and Whalen, 1987) demonstrated that samples of /s/ and /ʃ/ noises excerpted from children's fricative-vowel (FV) syllables were more difficult for adult listeners to distinguish than were adults' samples, but it was somewhat easier to identify the following vowel in the children's samples.

While Bickley (1980) has explored the possibility that it is inappropriate to describe children's vowel production using models of adult vowel production, we know of no similar investigation concerning children's fricative production. In fact, the few experiments that have investigated the acoustics of children's fricatives seem to consider (often implicitly) the articulatory patterns of children's fricative production to be identical to those of adults' production (e.g., Pentz *et al.*, 1979). This assumption predicts that the only difference between children's and adults' production lies in a spectral shift due to the difference in vocal tract size. We believe that there may be differences between children's and adults' fricative spectra that have other origins.

When looking through the magnitude spectra of children's (ages three to seven) utterances of /si/, /su/, /ʃi/, and /ʃu/ obtained in an earlier experiment (Nittrouer *et al.*, 1988), we consistently found a spectral prominence in the fricative portion of the utterance between 2200 and 3300 Hz, which we refer to as the "low-frequency peak." This prominence is not accounted for by a scaled version of the simplest theory of adult fricative production, which is described by Heinz and Stevens (1961) and Fant (1960). This model has its lowest frequency prominence at about 2500 Hz for adults' productions of /ʃ/, while the lowest frequency prominence for adults' /s/ is even higher in frequency. In this theory of fricative production, the cavity behind the constriction is completely decoupled from the rest of the system. The remaining cavities (i.e., the constriction and front cavity) are not sufficiently large for the production of resonances below 2500 Hz.

Nevertheless, adults do show small low-frequency peaks below 2500 Hz in the production of /s/ and /ʃ/, corresponding to the children's low-frequency peaks. These peaks in the 1600- to 2500-Hz range were measured by Soli (1981) to describe anticipatory coarticulatory effects in fricative-vowel syllables. He attributed them to resonances of the cavity behind the tongue tip's constriction and forward of the glottis. (We will refer to this cavity as the "back cavity.") Indeed, low-frequency resonances appear in models of the fricatives /s/ and /ʃ/ when a back cavity is coupled to the constriction of the simplest model described above. However, the amplitudes of these resonances are very small because they are closely associated with zeros. Further, the back cavity is, to a great degree, decoupled from the region anterior to the constriction, meaning both that it is decoupled from the sound source and that its resonant frequencies transmit poorly into the atmosphere (Heinz and Stevens, 1961; Fant, 1960; Shadle, 1985).

There appears to be no problem explaining the higher frequencies of these low-frequency peaks in children's as compared to adults' speech samples in terms of length scaling. However, the relatively higher amplitudes of the low-frequency peaks in children's /s/ and /ʃ/ samples cannot be so easily explained. The purpose of the present investigation was to carefully describe these spectral differences, and then to infer what young children might be doing differently from adults in their productions of /s/ and /ʃ/.

I. METHOD

A. Subjects

The speakers for the present experiment were a subset of those used in the earlier study (Nittrouer *et al.*, 1988). Twelve speakers from that experiment were chosen at random for this study: two children (one male and one female) at each of the ages 3, 4, 5, and 7 years, and four adults (two males and two females). All adult speakers were 20- or 21-years-old. All children were within − 1 and + 5 months of their birthdays. All speakers passed a hearing screening for the frequencies 500, 1000, 2000, and 4000 Hz presented at 20 dB HL, and had normal middle-ear pressure peaks between + 100 and − 150 daPa. All were monolingual speakers of American English from the Middle Atlantic region, and all children were judged to have normal articulation skills by two speech pathologists listening to recordings of spontaneous speech. Specifically regarding the purpose of this study, both /s/ and /ʃ/ were judged to be perceptually correct for all children.

B. Equipment

A Uher model 4200 portable tape recorder with an Electrovoice model 635A microphone was used for recording. This system had a flat frequency response (i.e., less than a 3-dB difference in amplitude) in the frequency range of 50 to 10 000 Hz. A Beltone model 9D portable audiometer and a Grason-Stadler model 27 portable tympanometer were used to screen hearing and check middle-ear function.

C. Procedure

Ten tokens of the utterances /ʃiʃi/, /sisi/, /ʃuʃu/, and /susu/ were collected in randomized groups of four from each subject. Utterances were spoken in response to pictures of a girl, referred to by the pronoun "she," of a boy pointing and saying "see," of a shoe, and of a girl named "Sue." The experimenter first provided a model for speaking the disyllables, using approximately the same rate, loudness, and intonation pattern with each subject. A brief practice session followed in which subjects were encouraged to produce tokens similar to the model, that is, without varying rate or loudness too greatly. While tokens for analysis were being collected, all responses were to the pictures only, and not to a model.

Eight tokens of each utterance from the selected speakers were digitized at 20 000 Hz, using a low-pass filter with a 9600-Hz cutoff. High-frequency preemphasis was not used. Vowel onset for each token was identified as the point at which periodicity first appeared in the waveform. The Haskins waveform editing program, WENDY, was used to extract two sections from each of these tokens. One section (file A) began 100 ms before the onset of the first vowel and extended 80 ms into the first vowel; the other section (file B) began 80 ms before the onset of the second vowel and extended 100 ms into the second vowel. Discrete Fourier transforms were done on each extracted file using 512-point (25.6-ms) Hamming windows at 6.4-ms intervals. The DFT files were then averaged together by utterance and section, resulting in eight files per speaker, four A's and four B's.

TABLE I. Frames selected for analysis and time (in ms) at which these frames were centered relative to vowel onset. Each frame extended for 12.8 ms to both sides of the time listed.

File A		File B	
Frame	Time	Frame	Time
1	− 87.2		
3	− 74.4	1	− 67.2
6	− 55.2	3	− 54.4
9	− 36.0	6	− 35.2
11	− 23.2	8	− 22.4
15	− 2.4	12	− 3.2
19	+ 28.0	16	+ 28.8
23	+ 53.6	20	+ 54.4
25	+ 66.4	24	+ 80.0

We picked spectral prominences by eye, and recorded the peak frequencies and amplitudes in dB at the selected analysis frames listed in Table I. These spectral prominences were labeled the second formant ($F2$), the third formant ($F3$), and the high-frequency maximum. For adults, $F2$ was often low in amplitude until 40 ms before vowel onset, making it difficult to identify. For both adults and children, $F2$ sometimes displayed broad bandwidths, making a precise peak frequency for $F2$ difficult to determine.

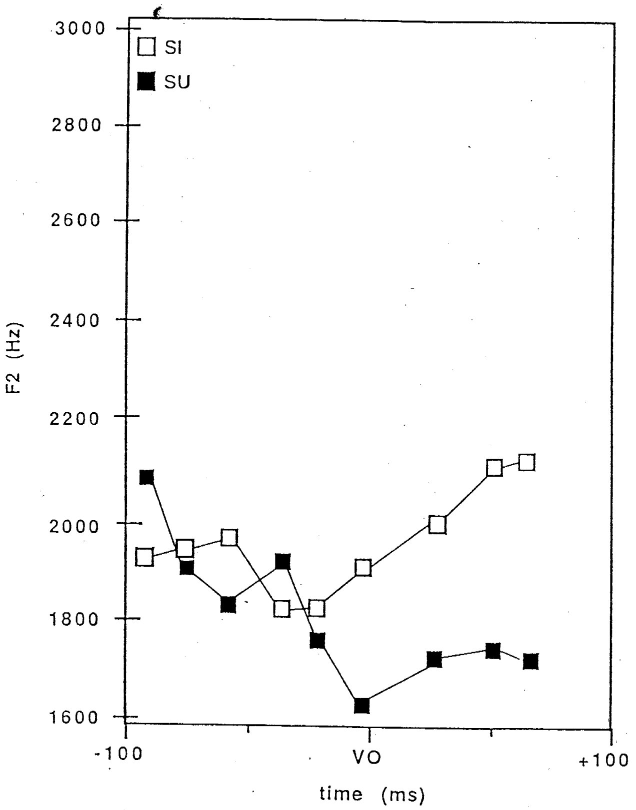

FIG. 1. The $F2$ (in Hz) for an adult male (subject AM2) taken from A files of /si/ and /su/ at selected analysis frames.

II. RESULTS

Figures 1–4 show $F2$ values for A files of /s/ at the selected analysis frames for two adults (one male and one female) and two children (the 7-year-old female and the 3-year-old male).[1] As illustrated in these figures, frequency values for fricative $F2$ were between 1600 and 2500 Hz for adults and between 2200 and 3300 Hz for children. The $F2$ label was used consistently to label what we call the low-frequency peaks.

In order to compare $F2$ values more precisely among age groups, and between male and female speakers, fricatives, and vowel contexts, we recorded the $F2$ values at frame 11 for the A series (23.4 ms before vowel onset) and at frame 8 for the B series (22.4 ms before vowel onset). These frames were chosen because the $F2$ peaks at these points were reliably identifiable for adults, and the frames were still completely within the fricative noise. Table II lists these fricative $F2$ values for individual subjects obtained from their A files, and Table III lists values obtained from their B files. Forty-three out of forty-eight comparisons show $F2$ frequency values for /ʃ/ to be above those for /s/, in samples with the same vowel. All female adults had $F2$ values above those of male adults, for identical utterances. Similarly, all children had $F2$ frequencies above those of all the adults, for identical utterances. In only 1 case out of a possible 48 was the fricative $F2$ of an utterance with vowel /u/ higher in frequency than the $F2$ of one containing /i/. This case also accounted for one of the instances in which the $F2$ of an /s/ was above that of an /ʃ/. The $F2$ in the fricative portion of /su/ for this

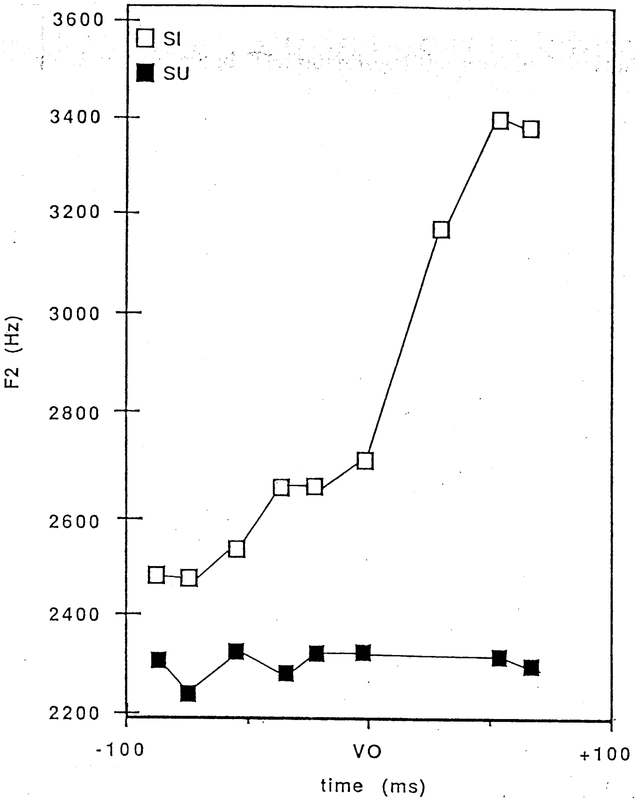

FIG. 3. The $F2$ (in Hz) for a 7-year-old female taken from A files of /si/ and /su/ at selected analysis frames.

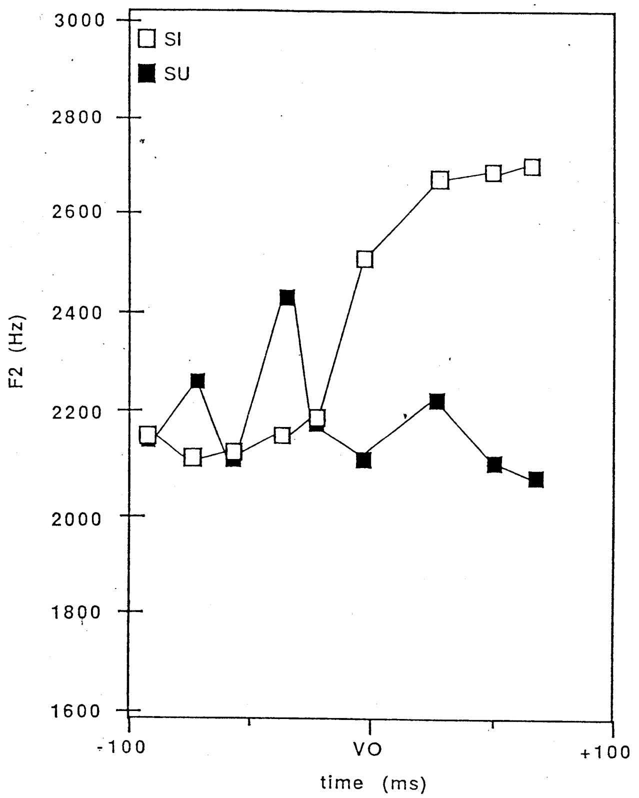

FIG. 2. The $F2$ (in Hz) for an adult female (subject AF2) taken from A files of /si/ and /su/ at selected analysis frames.

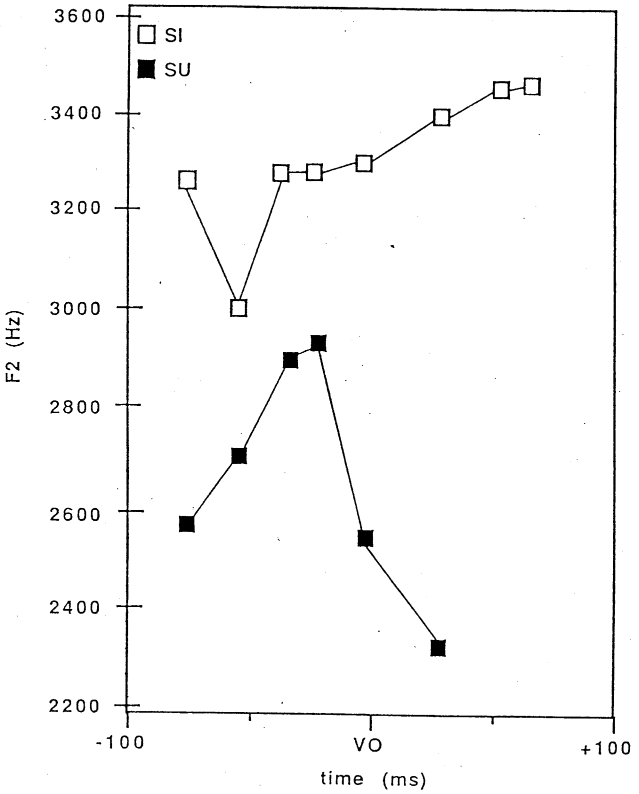

FIG. 4. The $F2$ (in Hz) for a 3-year-old male taken from A files of /si/ and /su/ at selected analysis frames.

TABLE II. The $F2$ values (in Hz) obtained from individual speakers in file A at frame 11. Speakers are identified by age and sex.

Utterance	ʃi	ʃu	si	su
Speaker				
AM1	1966	1850	1989	1713
AM2	1965	1931	1805	1747
AF1	2149	2115	2046	2241
AF2	2471	2471	2195	2172
7M	3069	2586	2517	2448
7F	2989	2701	2667	2333
5M	3011	2506	2586	2253
5F	3126	2402	2747	2644
4M	3195	2356	3057	1977
4F	3161	3149	2701	2264
3M	3023	2954	3276	2943
3F	3046	2793	2747	2506

TABLE III. The $F2$ values (in Hz) obtained from individual speakers in file B at frame 8. Speakers are identified by age and sex.

Utterance	ʃi	ʃu	si	su
Speaker				
AM1	2057	1851	1943	1644
AM2	1920	1874	1885	1724
AF1	2391	2115	2057	2080
AF2	2379	2310	2126	2103
7M	3138	2713	2713	2264
7F	2816	2632	2598	2310
5M	2655	2506	2506	2241
5F	3011	2667	2678	2448
4M	2862	2230	2586	2437
4F	3126	2874	2828	2471
3M	3115	2874	3057	2552
3F	2954	2701	2552	2310

speaker (a female adult) was simply higher than what we would expect.

In order to obtain a description of the relative strength of $F2$ compared to higher frequencies, we computed 20 log of the ratio of the amplitude of $F2$ to the amplitude of the high-frequency maximum for each average spectrum. This value was termed the relative $F2$ amplitude. Figures 5 and 6 illustrate means and ranges of these relative $F2$ amplitudes for children and adults for /s/ obtained from both A and B files. Figures 7 and 8 illustrate these means and ranges for /ʃ/.

III. DISCUSSION

Several patterns of results for $F2$ frequency values can be predicted from previous acoustic measurements and modeling. Because $F2$ is realized only when a back cavity is coupled to the constriction, and a tight constriction decouples the back cavity from the cavity in front of the constriction, $F2$ can be considered a back-cavity resonance (Shadle, 1985). We can predict that the frequency of $F2$ will increase with a decrease in back-cavity size. This explains the differences in location of $F2$ frequency between adult males and adult females, as well as the difference between adults and children. It also helps to explain the $F2$ frequency difference between /ʃ/ and /s/, because the location of the fricative constriction for /ʃ/ is posterior to the location of the constriction for /s/ (Perkell *et al.*, 1979). However, the configuration of the tongue body contributes to this difference as well in that the tongue body is higher and more fronted for /ʃ/ than for /s/ (Stevens, 1985; Stevens *et al.*, 1986; Fant, 1960).

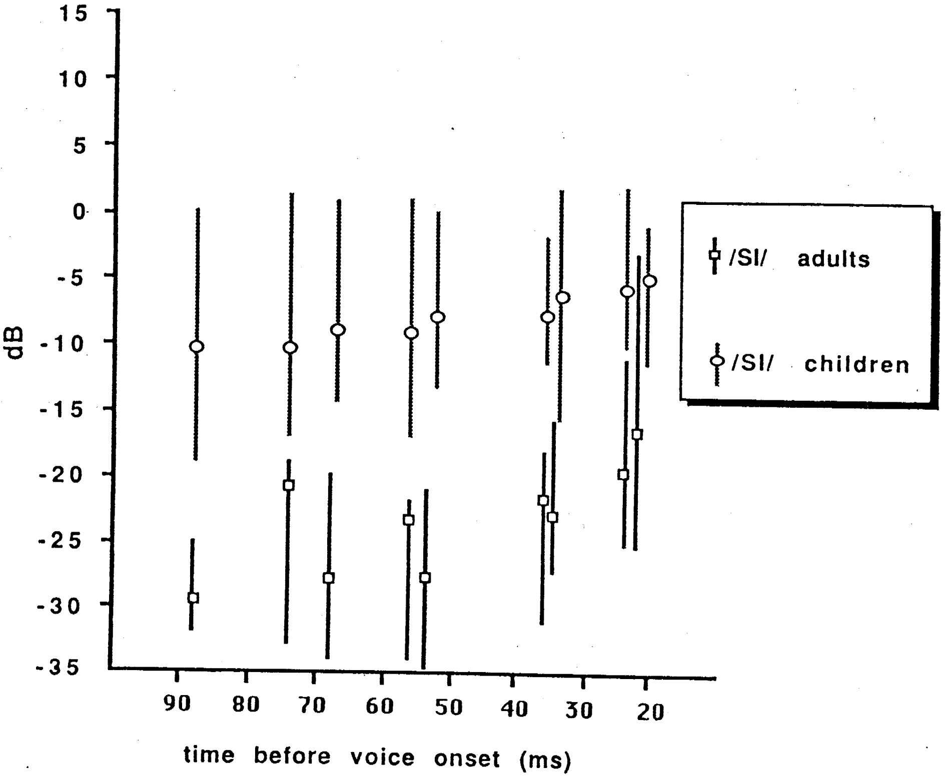

FIG. 5. Means and ranges for children and adults of relative $F2$ amplitudes taken from A and B files of /si/.

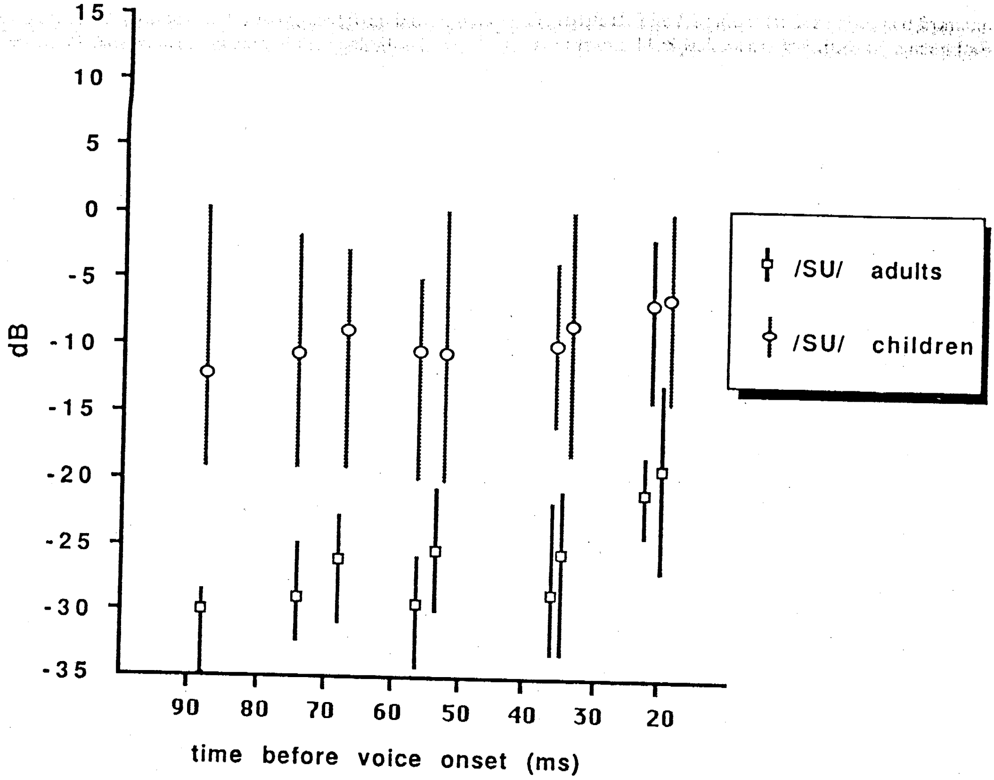

FIG. 6. Means and ranges for children and adults of relative $F2$ amplitudes taken from A and B files of /su/.

Some other patterns of results are not as easily explained. The difference in $F2$ frequency due to vowel context warrants closer examination. For all speakers, the fricative $F2$ preceding /i/ was higher in frequency than the fricative $F2$ preceding /u/ (with the one exception already noted). At least two possible explanations may be offered for this difference. First, liprounding during the fricative in anticipation of the upcoming /u/ lowers the frequency of all formants. Second, it is also possible that speakers position the tongue body, posterior to the fricative constriction, differently as a function of the upcoming vowel. Either of these possible explanations may entirely account for the difference in frica-

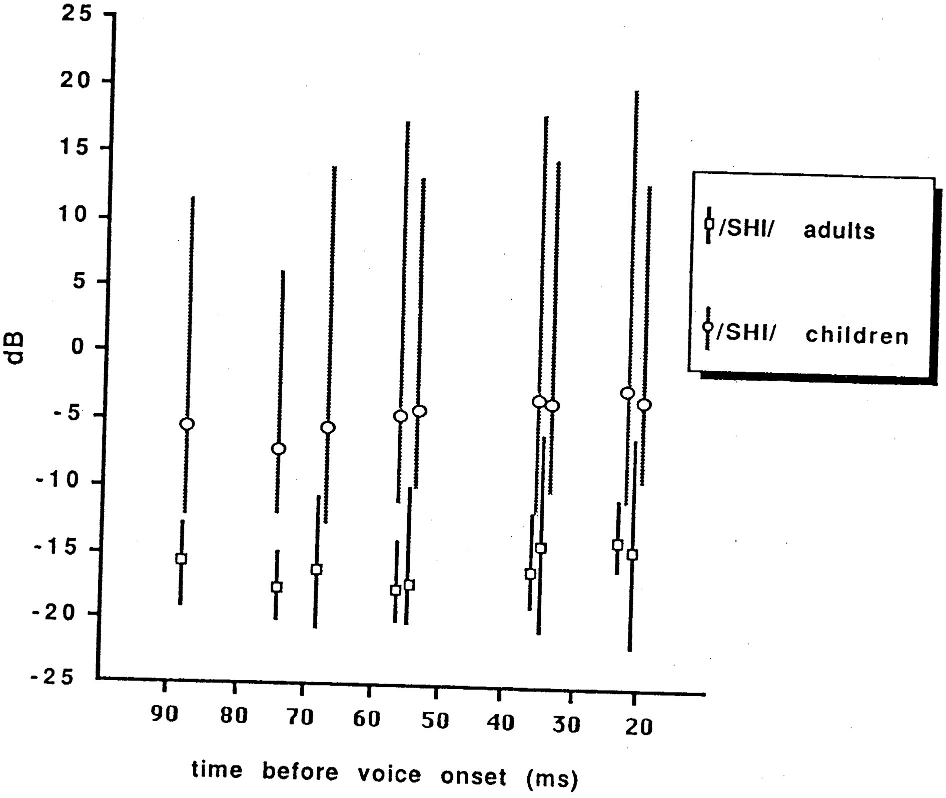

FIG. 7. Means and ranges for children and adults of relative $F2$ amplitudes taken from A and B files of /i/.

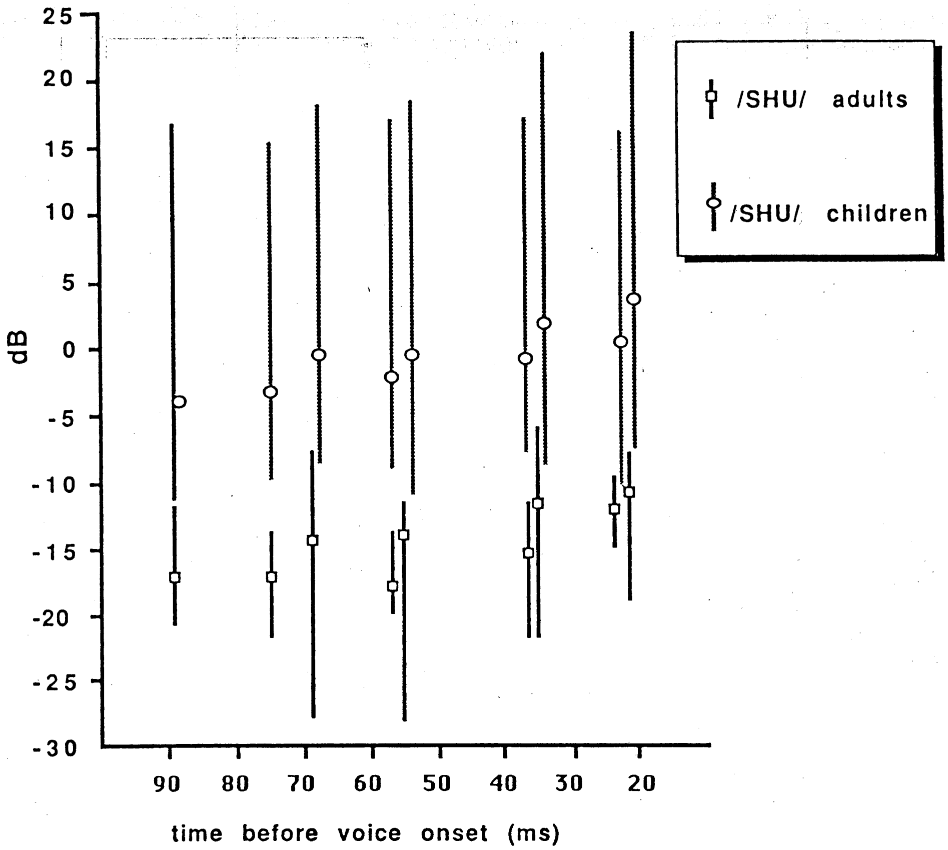

FIG. 8. Means and ranges for children and adults of relative $F2$ amplitudes taken from A and B files of /u/.

tive $F2$ values preceding /i/ and /u/; however, other work suggests that both explanations apply to some extent (Nittrouer *et al.*, 1988). At present, we do not have any articulatory data that could help determine their relative contributions.

The size of the vowel context effect varied with the age of the speaker. Children showed greater differences in fricative $F2$ frequency as a function of the following vowel than did adults. Therefore, regardless of the exact contribution of each of the above possible causes, it appears that children are doing something differently from adults to produce an enhanced vowel context effect (Nittrouer *et al.*, 1988). This observation requires closer physiological examination.

Differences were also observed between children and adults in relative $F2$ amplitude. Examination of Figs. 5–8 reveals that relative $F2$ amplitudes were generally higher for children than for adults. In the case of /s/, the extremes of the relative $F2$ amplitudes of the child and adult groups do not even overlap until the final frame before vowel onset. In the case of /ʃ/, the extremes do overlap earlier, but the average relative $F2$ amplitude of children is always greater than that of adults. For both children and adults, the relative $F2$ amplitude is higher for /ʃ/ than for /s/. Also, the relative $F2$ amplitudes for adults tend to increase with proximity to vowel onset. This last point can be explained simply by the greater coupling of the back cavity to the atmosphere that results as the fricative constriction is being released.

The observation that relative $F2$ amplitude is greater throughout the fricative for /ʃ/ than for /s/ can be explained partly by the amplifying effect that resonances have on one another as they come closer together (Fant, 1960). The $F3$ of /ʃ/ is amplified compared with the $F3$ of /s/; consequently, $F2$ will be greater in amplitude in /ʃ/ than in /s/. Also, there may be more coupling between the back cavity and the atmosphere for /ʃ/ than for /s/ because the constriction probably is not as narrow in the production of /ʃ/ as in the production of /s/ (Perkell *et al.*, 1979). Finally, Fant (1960) has noted that palatalization tends to separate the zero associated with the $F2$ pole. Since /ʃ/ is more palatal (or coronal) than /s/, this could also contribute to the greater relative $F2$ amplitude in /ʃ/ as compared to /s/.

The striking differences in the relative $F2$ amplitudes between children and adults cannot be explained by resonator size differences. One possibility would be to attribute the difference to the source spectrum. In the production of /ʃ/, the major source of sound is a fluctuating pressure source at the teeth. The spectrum of the source at the teeth is a function of the Strouhal number, which is the frequency times the ratio of the characteristic dimension of the teeth to the fluid particle velocity (Heller and Widnall, 1969). The relative $F2$ amplitude (in dB) is the difference in amplitude between frequencies, which are within a factor of two of each other, $F2$ and the high-frequency maximum. [The high-frequency maximum for /ʃ/ is generally below 3000 Hz for adults (Heinz and Stevens, 1961).] Using source spectra to account for differences in relative $F2$ amplitudes between children and adults for /ʃ/ would amount to saying that the region between $F2$ and the high-frequency maximum of the spectrum for children corresponds to a different range of Strouhal numbers than for adults.

We refer to the radiated source spectrum given by Heller and Widnall (1969), and used by Stevens (1971), for the flow over a spoiler in a pipe. Accounting for the relative $F2$ amplitude differences purely on the basis of Strouhal number changes would need the following scenario. The $F2$ would have to move from about or below a Strouhal number of 0.1 for adults to a Strouhal number of at least 1.0 for children (see Fig. 9). Because children's $F2$ frequency is about $\frac{3}{2}$ that of adults', this is equivalent to over a six times increase in the ratio of teeth characteristic dimension to fluid particle velocity. However, this gives a particle velocity for children at least ten times less than for adults, assuming children's teeth height to be at most $\frac{2}{3}$ that of adults (Goldstein, 1980). This would imply that the SPL of a child's /ʃ/ would be on the order of 60 dB less than that for an adult's /ʃ/, as SPL varies as the sixth power of particle velocity (Stevens, 1971). Any change in Strouhal number smaller than a factor of 10 would greatly diminish the importance of changes in the position of the source spectrum in accounting for differences in relative $F2$ amplitude because the source spectrum is so flat. We believe this disqualifies changes in source spectrum as the major contributor to the differences in relative $F2$ amplitudes in /ʃ/.

A similar argument applies to /s/. While there is a greater frequency difference between $F2$ and the high-frequency maximum for /s/ than for /ʃ/, pointing to a smaller necessary shift in Strouhal number, there is a greater difference in the relative $F2$ amplitudes, requiring a necessarily greater shift in Strouhal number. These results can be summarized by noting that the source spectrum is a gradual function of Strouhal number, and that large changes in the Strouhal number would be necessary to go from a region where the amplitude is an increasing function of Strouhal number for adults to where it is a decreasing function for children. Such a change would require too large a difference in SPL.

The large differences in relative $F2$ amplitudes seem to point either to a stronger source exciting the back cavity for children than for adults, or relatively better transmission of back-cavity sound to the atmosphere for children than for adults, or a combination of both.

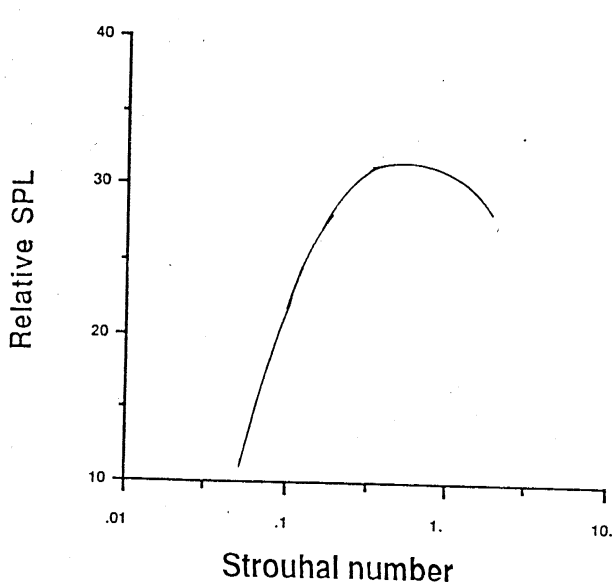

FIG. 9. Source spectrum as a function of Strouhal number.

The frication with which we are concerned is the result of turbulent flow interacting with solid surfaces. This is seen near the frication, or anterior, constriction as a resistance to flow. Even in adults, the glottis provides a resistance to the flow of air during fricative production because of its small area. This resistance is realized in turbulence production at the glottis, and a source of sound, just as the anterior constriction of the tongue tip or teeth provides turbulence-producing resistance in fricative production.

The strength of either the glottal source or the anterior source is determined by the kinetic pressure loss at the appropriate constriction. Kinetic pressure loss is proportional to the fluid particle velocity squared, and hence to the inverse square of area for a given volume velocity. Because the glottal resistor and anterior resistor are in series, the relative strengths of these sources are determined by the ratio of areas squared (Stevens, 1971). The larger the anterior constriction is compared to the glottal constriction, the stronger the glottal source is relative to the anterior source.

The size of the anterior constriction for any speaker is unknown, but we can get some idea of relative constriction sizes from pressure changes within the vocal tract. These pressure changes must be arrived at in an indirect way because subglottal pressure measurements have not been made for children. We can make an estimate of subglottal pressures by extrapolating from intraoral pressure measurements for /p/ and /b/ to an estimate of subglottal pressure for /s/ and /ʃ/. Stathopolous and Weismer (1985) found that children's peak intraoral pressure is about $\frac{3}{2}$ that of adults during the production of /p/ and /b/. Extrapolating from these results, subglottal pressure in the production of /ʃ/ and /s/ is probably greater for children than for adults. Measurements made by Goldstein (1980) indicate that the lengths of children's vocal folds (ages 3 to 7) are about $\frac{1}{3}$ those of adult males. Because of this, it is reasonable to assume that differences in the child's glottal area compared to the adult's glottal area could account for any additional subglottal pressure and, perhaps, account for even more of the total pressure drop. This also implies that the square area of the children's anterior constrictions would be at least half as large as the square area of their glottal constrictions, and the relative strengths of children's glottal sources should be at least half again as strong as that of adults. More pressure measurements are needed before more precise statements can be made about the relative sizes of the sources. However, the child's glottis is small enough to give credibility to the notion of a stronger glottal source relative to the source at the anterior constriction.

Even if we accounted for the relative $F2$ amplitude differences by hypothesizing a greater coupling between back cavity and atmosphere, we would also conclude that the strength of the glottal source is increased compared to the strength of the anterior source for children as compared to adults. Better coupling requires a larger anterior constriction area, and thus a weakening of the anterior source for a given glottal source strength.

By adding strength to the glottal source, we tend to distribute the frication source in space. This has the effect of reducing the importance of spectral zeros because zeros depend on source location, as well as the cavity configuration. Canceling the spectral zero associated with $F2$ will enhance the $F2$ amplitude. In fact, we had difficulty locating zeros in the children's spectra that we examined.

Finally, we make a qualitative observation. Children show variability in higher formant frequency bandwidths when viewed in spectrograms. In other words, the high-frequency portions of children's spectra are noisier than the high-frequency portions of adults' spectra. This may be due to aspiration noise that occurs during phonation, caused by a small glottal opening.

IV. CONCLUSION

We have found that, while the generally higher frequency values of children's $F2$'s (ages 3 to 7) can be explained as scaled frequencies of adults' $F2$'s, the greater amplitudes depend on other details of children's anatomy. In particular, the back-cavity resonance is more prominent in children's fricative spectra than in adults'. This prominence seems to be caused by a relatively stronger glottal source in children than in adults. While there may be better coupling between the back cavity and atmosphere in children than in adults, again, this can only heighten the importance of the glottal source in children. Pressure measurements would be needed to find, precisely, the relative importance of the glottal and anterior sources. The observation of the importance of the glottal noise source may generalize to voiced sounds, which would result in noisier spectra in the high frequencies than would otherwise be expected. Finally, the enhanced vowel context effect found for children's $F2$ values compared to adults' $F2$ values indicates that there are other physiological differences between children's and adults' fricative production. A complete description of these physiological differences awaits further production studies of children's speech.

ACKNOWLEDGMENTS

This work was supported by NIH Grants NS-13617 and NS-07237 to Haskins Laboratories. The authors would like to thank Professor Ronald Baken for references on physiological measurement and Professor K. N. Stevens for a helpful discussion on fricatives. The comments on earlier drafts of this article by Bruno Repp, Michael Studdert-Kennedy, D. H. Whalen, and an anonymous reviewer are also gratefully acknowledged.

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[1] The $F2$ values were not recorded for all analysis frames for this 3-year-old male because his fricatives were shorter than 100 ms, and because his $F2$ in /u/ merged with $F1$ shortly after vowel onset.

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