

Effect of stimulus bandwidth on the perception of /s/ in normal- and hearing-impaired children and adults

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Recent studies with adults have suggested that amplification at 4 kHz and above fails to improve speech recognition and may even degrade performance when high-frequency thresholds exceed 50–60 dB HL. This study examined the extent to which high frequencies can provide useful information for fricative perception for normal-hearing and hearing-impaired children and adults. Eighty subjects (20 per group) participated. Nonsense syllables containing the phonemes /s/, /f/, and /θ/, produced by a male, female, and child talker, were low-pass filtered at 2, 3, 4, 5, 6, and 9 kHz. Frequency shaping was provided for the hearing-impaired subjects only. Results revealed significant differences in recognition between the four groups of subjects. Specifically, both groups of children performed more poorly than their adult counterparts at similar bandwidths. Likewise, both hearing-impaired groups performed more poorly than their normal-hearing counterparts. In addition, significant talker effects for /s/ were observed. For the male talker, optimum performance was reached at a bandwidth of approximately 4–5 kHz, whereas optimum performance for the female and child talkers did not occur until a bandwidth of 9 kHz. © 2001 Acoustical Society of America. [DOI: 10.1121/1.1400757]

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I. INTRODUCTION

A number of studies have suggested that some listeners with sensorineural hearing loss may receive limited benefit from amplification in the high-frequency region. Specifically, it has been reported that systematic increases in high-frequency gain may not improve, and in some cases may degrade, speech recognition for listeners with steeply sloping high-frequency hearing losses (Skinner, 1980; Murray and Byrne, 1986; Rankovic, 1991; Ching, Dillon, and Byrne, 1998; Hogan and Turner, 1998; Turner and Cummings, 1999). The results of these studies have important implications for clinical practice. If amplifying speech to audible levels in the high frequencies does not improve speech recognition, then attempts to provide gain may not be necessary or desirable in certain cases. While the studies cited above appear to support the general notion that high-frequency amplification may not always be beneficial, the intersubject variability in most studies precludes a clearly defined rule that would distinguish listeners who are likely to benefit from high-frequency amplification from those who are not. Furthermore, differences in subject selection, filter conditions, and methodology across studies complicate the interpretation of results.

For example, Murray and Byrne (1986) assessed the effects of low-pass filtering at five frequencies (from 1.5–4.5 kHz) on judgments of intelligibility and pleasantness for continuous discourse. Subjects were normal-hearing (NH) and hearing-impaired (HI) adults with steeply sloping losses above 1 kHz. Although all of the NH subjects preferred the widest bandwidth, three of the five HI subjects preferred the 2.5- or 3.5-kHz bandwidth over the 4.5-kHz bandwidth. Because “judged” intelligibility was used in this study, the effects of low-pass filtering on objective measures of speech recognition were not described. Skinner (1980) used a high-

frequency monosyllabic word list to assess the speech recognition ability of six adults with steeply sloping losses. Stimuli were filtered using five different frequency responses with increasing gain in the 1–8-kHz region. Results indicated that a frequency response with intermediate high-frequency gain was best for understanding speech at a conversational level. However, the two responses with the greatest high-frequency gain were best for understanding low-level speech. Ching *et al.* (1998) assessed recognition of filtered sentences in hearing-impaired adults and compared results to predictions based on variants of the Speech Intelligibility Index. Audible energy in the high-frequency region (2.8–5.6 kHz) contributed no information or actually decreased performance for listeners with thresholds >80 dB HL at 4 kHz. The majority of listeners with thresholds in the 50–80-dB HL range, however, benefited from audible signals in this high-frequency region.

Hogan and Turner (1998) also investigated the effects of stimulus bandwidth on phoneme recognition in listeners with steeply sloping hearing losses. Nonsense syllables were frequency shaped and low-pass filtered at 12 cutoff frequencies from 0.56 to 9 kHz. The benefit of providing additional high-frequency audibility was negligible or negative when the degree of loss at and above 4 kHz exceeded 55 dB HL. In some cases, performance decreased with increases in high-frequency audibility. In a similar study, Turner and Cummings (1999) investigated the benefit of high-frequency information in listeners with varying degrees and configurations of hearing loss. Recognition was evaluated as a function of increasing high-frequency information for nonsense syllables presented over a range of levels above and below threshold. Results confirmed the earlier findings that listeners with hearing loss ≥ 55 dB HL at and above 4 kHz did not benefit from high-frequency information. In contrast to some

of the previous studies, however, increased gain in the high-frequency region did not degrade performance.

In interpreting the results of these filtering experiments, it is important to consider the test stimuli. For example, Murray and Byrne (1986) and Ching *et al.* (1998) used sentences as the test materials. A study by Studebaker, Pavlovic, and Sherbecoe (1987) suggests that, when contextual information is available, the frequency region of maximum importance is between 0.4 and 5 kHz. Thus, high-frequency audibility may not be as critical to the perception of sentence materials as it would be for less linguistically complex speech materials. The stimuli used in the Hogan and Turner (1998) and Turner and Cummings (1999) studies contained a relatively large proportion of phonemes (e.g., /b,d,g,l,m,n,r,dʒ/) that can be perceived from mid- and low-frequency cues. Reduced performance for the small number of phonemes comprised primarily of high-frequency energy (e.g., /s,ʃ,z/) may not have influenced overall scores significantly. Although an error analysis was not reported for these two studies, a similar investigation by Sullivan *et al.* (1992) found large improvements in performance (30%–45%) for the phonemes /s,ʃ,z/ as stimulus bandwidth was increased, despite nonsignificant differences in the overall scores for the different filter conditions.

Of these high-frequency fricatives, /s/ is known to be linguistically important. It is the third or fourth most frequently occurring phoneme in the English language and serves multiple linguistic functions, including plurality, tense, and possession (Tobias, 1959; Denes, 1963; Rudmin, 1983). Among both adults and children with hearing loss, /s/ is one of the most frequently misperceived phonemes (Owens, Benedict, and Schubert, 1972; Bilger and Wang, 1976; Owens, 1978; Dubno and Dirks, 1982; Danhauer *et al.*, 1986). In addition, Elfenbein, Hardin-Jones, and David (1994) have reported that the language samples of children with mild-to-moderate hearing loss often include increased errors in both noun and verb morphology (e.g., cat versus cats, keep versus keeps). It is likely that these findings are related to a reduction in audibility of the fricative noise and/or the vocalic transition in the presence of hearing loss. For adults with acquired hearing loss, there may be sufficient linguistic and redundant acoustic cues to compensate for this loss of audibility. When the hearing loss is congenital or acquired in early life, the reduction in audibility may be more problematic. Kortekaas and Stelmachowicz (2000) investigated the effects of low-pass filtering on the perception of /s/ in NH children (5-, 7-, and 10-year-olds) and adults. They found that the children required a wider signal bandwidth than did adults to perceive /s/ correctly when stimuli were presented in noise. To our knowledge, no studies have been conducted with HI children. If similar findings were observed in hearing-impaired children, restricting the bandwidth of speech may have a negative impact on speech and language development in young HI children.

The methodology used in the previous adult studies may not be ideal to address the effects of high-frequency amplification in young HI children. For example, subjective estimates of speech perception have poor test–retest reliability and do not correlate well with performance measures (Byrne,

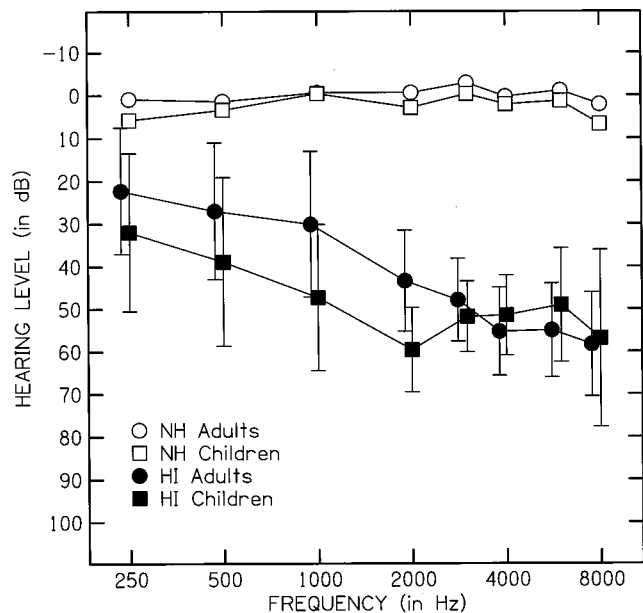


FIG. 1. Hearing thresholds as a function of frequency for the NH adults and children (open symbols) and the HI adults and children (filled symbols). Error bars (± 1 standard deviation) are shown for the HI listeners only.

1986; Gabriellson, Schenkman, and Hagerman, 1988; Studebaker and Sherbecoe, 1988). Objective measures of performance using words and/or sentences also are problematic because the child's auditory experience and language competence may have an influence on test performance. Nonsense syllables circumvent these problems, but given that performance in the Sullivan *et al.* (1992) study differed across stimuli, it would seem reasonable to restrict the items to those that contain high-frequency information. It would also be most useful to focus on sounds that are important to speech and language development. The purpose of the present study was to determine the effect of stimulus bandwidth on the perception of /s/ in NH and HI children and adults. These four groups of subjects were included to separate the effects of hearing loss from general development.

II. METHODS

A. Listeners

A total of 80 listeners participated in this study. The two NH groups were comprised of 20 adults (ages 19–43 years, $M=28$ years) and 20 children (5–8 years, $M=7$ years, 3 months). The two HI groups also consisted of 20 adults (26–65 years, $M=56$ years) and 20 children (5–8 years, $M=7$ years, 1 month). The NH listeners had pure-tone thresholds ≤ 15 dB HL for the octave frequencies from 0.25 to 8 kHz. The HI listeners had moderate to moderately severe sensorineural hearing losses that ranged between 40 and 70 dB HL at 2 and 4 kHz. Figure 1 shows the mean pure-tone thresholds for each group (± 1 s.d. are shown for the HI listeners only). Based upon available audiological data and subjective history, all of the HI children had congenital losses and the HI adults had acquired their losses later in life. All listeners had normal middle-ear function at the time of testing.

B. Stimuli

Although the primary interest of this study was the perception of /s/, it was necessary to provide subjects with alternative stimuli that would be easily confused with /s/. A pilot study with NH adults indicated that filtered versions of /s/ were most likely perceived as either /f/ or /θ/. Thus, the test stimuli were consonant–vowel (CV) and vowel–consonant (VC) syllables comprised of the phonemes /s/, /f/, and /θ/ in an /i/ vowel context. The /i/ vowel was used to minimize the vocalic transition which might be used as a cue to distinguish the fricatives from one another. In addition, multiple repetitions of each sample were obtained from all three talkers, and samples with little or no transition were selected as stimuli for the study. The CV and VC syllables were produced by an adult male, an adult female, and a 6-year-old child (for a total of 18 stimuli). All speech samples were recorded in a sound-treated room at normal vocal levels using a microphone with a flat frequency response to 10 kHz (AKG Acoustics, C 535EB). The speech samples were amplified, filtered at 10 kHz, and digitized at a sampling rate of 20 kHz. The 18 syllables were edited to ensure equivalent rms levels (of the entire syllable) across all stimuli. The stimuli were analyzed in 17 1/3-octave bands (TOB) with a 20-ms Hanning window (50% overlap) after being transduced by the earphone (Sennheiser 25-1) and recorded in a flatplate coupler. Figure 2 shows the relative TOB spectra for the /s/, /f/, and /θ/ in the CV context for each talker. The spectrum for each phoneme in the final position showed a similar pattern. The spectral characteristics of /s/ varied markedly across talkers. Relative to the female talker, more mid-frequency energy was apparent for the male and child talkers. These spectral characteristics are consistent with previous data for this phoneme (Stevens, 1960; Heinz and Stevens, 1961; McGowan and Nittrouer, 1988; Nittrouer, Studdert-Kennedy, and McGowan, 1989; Boothroyd and Medwetsky, 1992; Boothroyd, Erickson, and Medwetsky, 1994; Jongman, Wayland, and Wong, 2000). The peak energy for both /f/ and /θ/ was lower in amplitude than for /s/ and talker differences were only observed for /f/ where the fricative amplitude for the child talker was approximately 10 dB higher than the other talkers. In the final consonant position, fricative amplitude for the child talker was higher only for /θ/.

To determine the influence of bandwidth on the perception of high-frequency voiceless fricatives, each syllable was low-pass filtered with a rejection rate of 50 dB/octave at six frequencies (2, 3, 4, 5, 6, and 9 kHz). Additional filtering for purposes of antialiasing was not necessary because the sampling rate of these syllables was greater than twice the widest bandwidth condition.

C. Procedure

All testing was conducted in a sound-treated room. The nonsense syllables were presented monaurally through the same earphone used to obtain hearing thresholds (Sennheiser, 25-1). Each listener was instructed to indicate which nonsense syllable was presented by touching the appropriate box on a touch-screen monitor or by selecting it

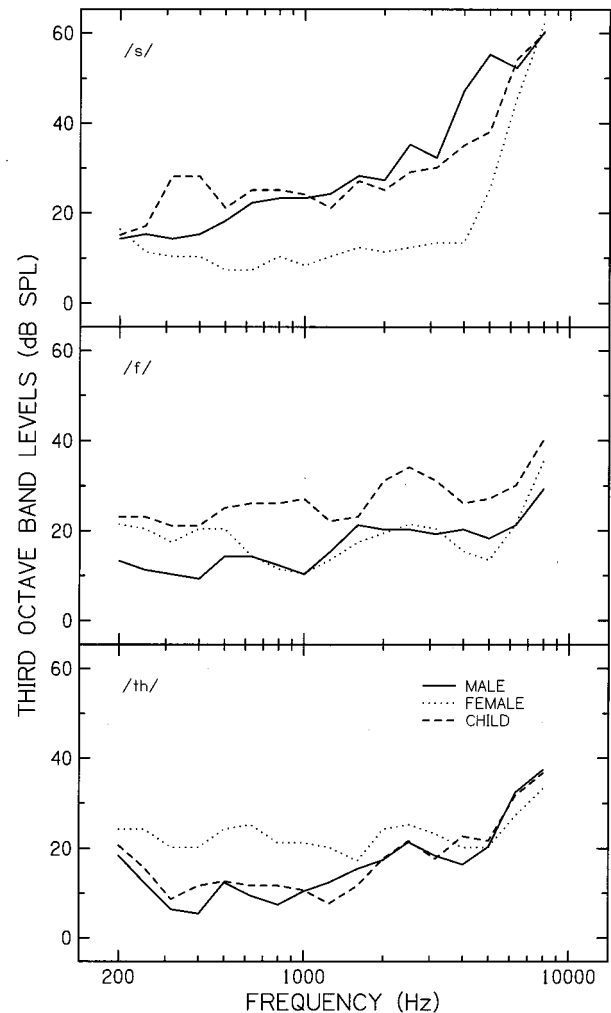


FIG. 2. Relative levels of the fricative noise in 1/3-octave bands for the utterances /si/, /fi/, and /θi/ as a function of frequency for the male, female, and child talkers.

with a mouse. The response boxes were labeled “s,” “f,” and “th.” Prior to testing, each child was asked to read or identify the orthographic form of the phonemes (/s/, /f/, and /θ/). The children were also shown pictures of words that contained these phonemes in the initial and final position and asked to identify them. Children who were unfamiliar with the orthographic forms of the phonemes, but could clearly produce them, were instructed to repeat the syllables so that the examiner could vote for the child. Those children who were unable to correctly produce the phonemes or identify their orthographic forms were excluded from the study.

The syllables were divided into CV and VC subtests. For each subtest, stimuli were presented 10 times for a total of 540 trials (6 filter conditions \times 3 talkers \times 3 fricatives \times 10 repetitions). On any given trial, one of 540 stimuli could occur. This form of randomization was used to limit the loudness cues that might be present if each low-pass filter condition were tested separately. For example, at a 9-kHz band /s/ would be louder than either /f/ and /θ/. When randomized, /f/ and /θ/ filtered at 6 or 9 kHz could actually sound louder than an /s/ filtered at 2 kHz. Software was written in MATLAB (Mathworks) to randomly select the test

stimuli and filter condition. The program also was used to reinforce correct responses in a video game format. Both the children and adult listeners were tested with the same procedure. For the NH listeners, the syllables were presented at a level equivalent to soft speech (45 dB SPL). For the HI listeners, the stimuli were altered to provide frequency/gain characteristics as recommended by the desired sensation level procedure for soft speech (53 dB SPL) (Seewald *et al.*, 1997).

III. RESULTS AND DISCUSSION

Although data were collected for /s/, /f/, and /θ/, the primary interest of this study was the proportion of /s/ responses to the /s/ stimuli. Accordingly, results for /f/ and /θ/ are given only for comparison when necessary. To ensure that a stimulus bias toward /s/ did not occur, the data were screened to determine that the proportion of /s/ responses was appropriate. Collapsed across all filter conditions, the proportion of /s/ responses for all groups (28%–34%) was consistent with the fact that /s/ was presented in 33% of the trials. Given that no biases were observed, scores for /s/ were arcsine transformed to normalize the variance across performance levels and analyzed with a repeated-measures analysis of variance (ANOVA). Talker (male, female, and child), filter (2, 3, 4, 5, 6, and 9 kHz), and position (VC and CV) were the within-subjects factors and hearing (normal and hearing impaired) and age (child and adult) were the between-subjects factors. A Greenhouse–Geisser correction was used to adjust the degrees of freedom for those conditions that failed to meet the assumption of sphericity (Max and Onghena, 1999). Significant main effects were found for talker [$F(1.895,143.9)=444.99$; $p<0.01$] and filter [$F(5,380)=291.49$; $p<0.01$], but not for consonant position [$F(1,76)=0.80$; $p=0.37$]. In addition, the between-subjects factors revealed a significant effect of hearing [$F(1,76)=37.98$; $p<0.01$] and age [$F(1,76)=11.42$; $p<0.01$] with no hearing×age interaction [$F(1,76)=0.38$; $p=0.54$].

Since no significant differences in performance were found between the VC and CV conditions, data were collapsed across the two subtests. In Fig. 3, performance as a function of low-pass frequency is shown for the male, female, and child talkers with group as the parameter. In the top panel (male talker), performance for the NH children and adults exceeded 80% at a filter frequency of 4 kHz. In contrast, performance for the HI children and adults did not exceed 80% until a cutoff frequency of 5 kHz. For the female talker (middle panel), performance was near chance (33%) through 5 kHz for all groups, with an abrupt increase in performance at 6 kHz for the NH listeners and at 9 kHz for the HI listeners. All four groups reached optimum performance at 9 kHz, with the two NH groups and HI adults achieving >80% performance and the HI children achieving only 77%. This finding is not surprising given the narrow region of spectral energy for the female /s/. A different pattern was observed for the child talker (lower panel). As bandwidth increased, a more gradual improvement in performance was observed for all groups, with the NH groups and HI adults achieving $\geq 80\%$ performance at the 9-kHz cutoff frequency. The performance of the HI children, however,

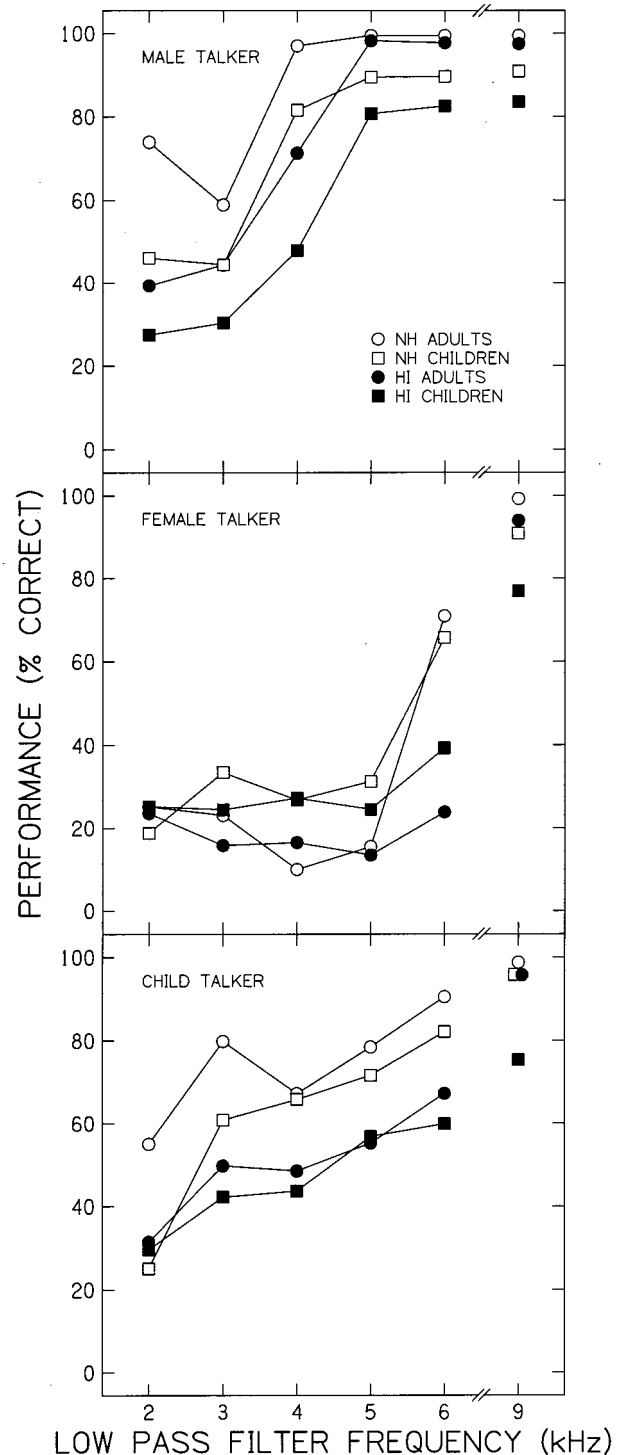


FIG. 3. Mean data illustrating percent correct as a function of low-pass filter frequency for the male (top panel), female (middle panel), and child (lower panel) talkers. The parameter in each panel is group.

only reached 75% at the widest bandwidth. For all groups and all talkers, mean performance increased as a function of bandwidth with no evidence of a decrease in performance as bandwidth widened. Inspection of the 60 individual performance intensity functions (3 talkers×20 listeners) for the HI adults revealed no evidence of nonmonotonicity, whereas three of the 60 functions for the HI children showed a statistically significant decrease in performance at the widest bandwidth.

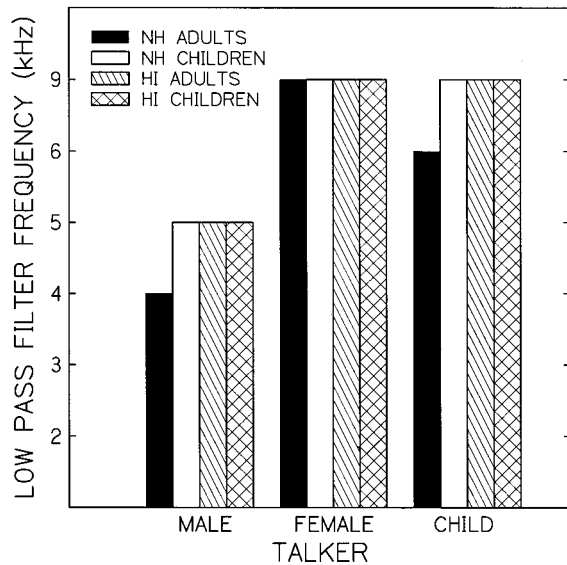


FIG. 4. Mean data showing the minimum low-pass filter frequency at which optimum performance was achieved by each group as a function of talker.

From a clinical perspective, it is of interest to determine the minimum bandwidth at which optimum performance was achieved for each group. Accordingly, the plateau portion of each function in Fig. 3 was defined as the range of bandwidths where data points were within $\pm 5\%$ of each other. The lowest frequency on the plateau was designated as the minimum bandwidth at which optimum performance occurred. The results for each group are shown as a function of talker in Fig. 4. For the male talker, optimum performance for the NH adults was achieved at a mean frequency of 4 kHz, whereas all other groups required a frequency of 5 kHz. For the female talker, performance continued to improve at a bandwidth of 9 kHz for all groups. For the child talker, the plateau occurred at 6 kHz for the NH adults and at 9 kHz for all other groups.

To compare performance across conditions in terms of stimulus sensation level, a measure of short-term audibility (STA) for the fricative portion of each utterance was calculated for all stimuli, filter conditions, and talkers using the following formula:

$$STA = \frac{1}{15} \sum_{i=1}^{17} (TOB_i - \theta_i) W,$$

where i is the center frequency of each 1/3-octave band, TOB is the 1% peak level of the fricative noise for each 1/3-octave band, θ is the hearing threshold in dB SPL for each TOB, and W is equal to 0.059, representing equal weights across the 17 bands (from 0.2–8 kHz). The sum of the weighted sensation levels was restricted to a 0- to 15-dB range by the multiplier 1/15. Previous studies have shown that the 30-dB range typically used for calculation of the Articulation Index is inappropriate for shorter segments of speech (Pittman and Stelmachowicz, 2000). Table I shows mean STA and performance for each group at the bandwidth where optimum performance was achieved. Because the audibility of /f/ and /θ/ may influence the performance for /s/, results for these stimuli are provided for comparison. For all phonemes,

TABLE I. Mean short-term audibility (STA) at optimum performance for all phonemes and talkers.

	Male		Female		Children	
	STA	%	STA	%	STA	%
/s/						
NH adults	0.42	100	0.26	99	0.53	98
NH children	0.50	91	0.22	91	0.46	91
HI adults	0.26	98	0.18	94	0.23	96
HI children	0.28	84	0.15	77	0.17	75
/f/						
NH adults	0.35	95	0.22	66	0.39	84
NH children	0.26	78	0.15	56	0.32	73
HI adults	0.12	87	0.08	59	0.25	72
HI children	0.08	60	0.05	55	0.19	51
/θ/						
NH adults	0.26	47	0.38	93	0.39	60
NH children	0.12	41	0.25	73	0.31	45
HI adults	0.08	46	0.11	59	0.20	51
HI children	0.06	32	0.07	35	0.13	30

optimum performance was consistently lower for the two groups of children relative to their adult counterparts and optimum performance for the NH listeners exceeded that of their HI counterparts. For /s/, performance was well above chance (33%) for all groups and talkers. Consistent with the findings of Pittman *et al.* (2000), the HI adults achieved similar performance to the NH adults but at substantially lower STA levels. Unlike the results of Pittman *et al.*, however, the HI children were not able to correctly identify /s/ as well as their adult counterparts at low STA values. This may be due to the fact that the children in the current study were younger (5–8 years) than in the earlier study (8–11 years). For /f/ and /θ/, performance was well above chance in most cases even when STA values were low. The one exception is the HI children's chance performance for /θ/. This may be related to the fact that /θ/ has a low frequency of occurrence in the English language (Denes, 1963) and thus, young HI children may be less familiar with this phoneme.

It is also of interest to determine if the degree of hearing loss in these listeners influenced their ability to use high-frequency speech information. Recall that previous studies found high-frequency information to be of limited benefit for individuals with hearing loss ≥ 55 dB HL at and above 4 kHz (Hogan and Turner, 1998; Turner and Cummings, 1999). To determine if degree of hearing loss influenced the results in the present study, each of the two HI groups was subdivided into listeners with thresholds ≥ 55 dB HL and < 55 dB HL at 4 kHz. Figure 5 shows mean performance as a function of low-pass frequency with degree of hearing loss as the parameter. Performance is similar for both categories of hearing loss and there is no evidence of decreased performance at the widest bandwidths. To ensure that this arbitrary grouping (at 55 dB HL) did not obscure trends associated with degree of hearing loss, the relation between performance and hearing level was inspected at each low-pass filter frequency. No systematic trends were observed for either HI group. It is worth mentioning, however, that the maximum hearing loss at 4 kHz did not exceed 70 dB HL in this study; inclusion of

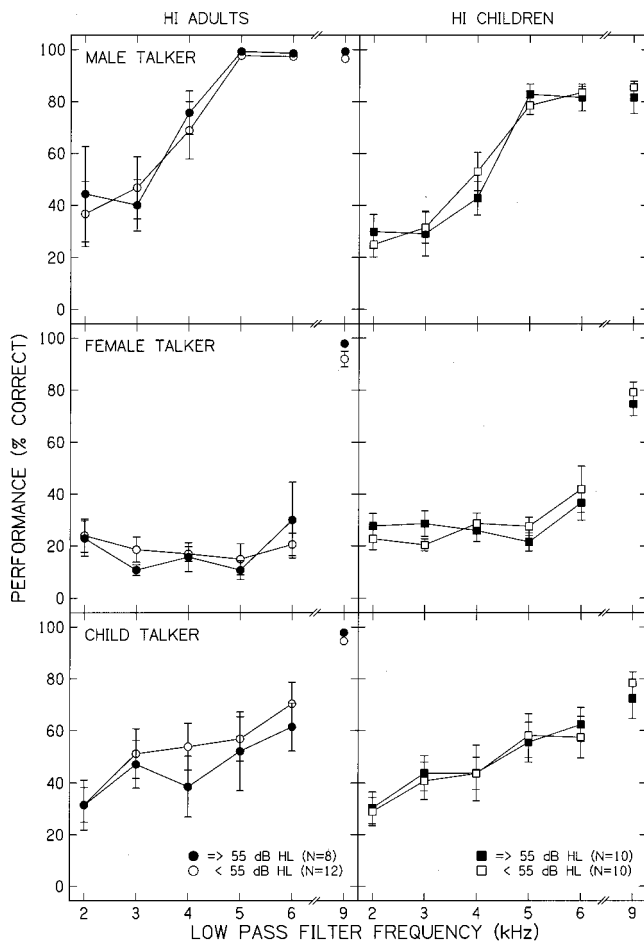


FIG. 5. Data for the HI listeners from Fig. 3 are replotted to illustrate the effects of degree of hearing loss. In each panel, results are shown for listeners with hearing loss at 4 kHz ≥ 55 dB HL (filled circles) or < 55 dB HL (open circles). Error bars represent the variance about the mean.

individuals with more severe hearing losses may have yielded different results.

IV. GENERAL DISCUSSION

This study found significant differences in the perception of /s/ across the NH and HI adults and children. Optimum performance for the children was poorer than for the corresponding groups of adults. This finding is consistent with other studies in which the performance of adults and young children were compared. Specifically, developmental differences have been observed for a variety of auditory tasks including detection, masked thresholds, temporal processing, frequency discrimination, and speech recognition (Nozza and Wilson, 1984; Schneider *et al.*, 1989; Allen *et al.*, 1989; Wightman *et al.*, 1989; Veloso, Hall, and Grose, 1990; Nozza, Rossman, and Bond, 1991; Hnath-Chisolm *et al.*, 1998). In addition, the HI groups performed more poorly than their NH counterparts despite the frequency/gain shaping provided in accordance with the desired sensation level procedure (Seewald *et al.*, 1997). These results suggest that both age and hearing loss affect the perception of /s/ under filtered conditions, with young HI listeners at the greatest disadvantage.

The patterns of performance observed across the three talkers may have important implications for speech and language development in infants and children with hearing loss. Recall that for the male talker, the NH adults achieved optimum performance at a filter frequency of 4 kHz while the NH children and both groups of HI listeners required a somewhat wider bandwidth (5 kHz). For all subjects, mean performance for the female and child talkers continued to improve as the bandwidth increased to 9 kHz with no evidence of degradation. Until recently, most commercially available hearing aids have provided minimal amplification above 4 kHz. Even with advanced signal processing and feedback reduction schemes, very little gain is provided for frequencies above 5 kHz. Thus, it is likely that the peak energy of a female /s/ may not always be audible to hearing-aid users. Further, a young HI child may hear the plural form of certain words more often when spoken by a male. Since infants and preschool children tend to spend most of their waking hours with female caregivers and other children, they may experience inconsistent exposure to /s/ across different talkers, situations, and contexts. Because many of the linguistic functions of /s/ in the English language are rather subtle (e.g., “Is that Beth?” versus “Is that Beth’s?;” “She put it on” versus “She puts it on”), inconsistent audibility of /s/ during the early years of life may influence or delay the formation of linguistic rules.

Boothroyd and Medwetsky (1992) have suggested that hearing aids may require an upper limit of 10 kHz to ensure the audibility of /s/ for female talkers. Theoretically, with the selection of an appropriate receiver and an earmold carefully constructed to minimize feedback, the upper frequency limit could be extended to 7–8 kHz. Although manufacturers often report that the upper bandwidth of current hearing aids is > 6 kHz, the upper- and lower-frequency range is defined as the 20-dB down point relative to the average gain at 1000, 1600, and 2000 Hz (ANSI, 1996). Thus, a hearing aid with an average use gain of 40 dB would only have 20 dB of gain at the upper frequency limit. In many cases, this may be inadequate to ensure the audibility of /s/. In addition, acoustic feedback will often limit usable gain due to factors such as intentional venting, imperfect seal of the earmold, leaks at tubing joints, and emission from tubing walls (Hellgren, Lunner, and Arlinger, 1999). Acoustic feedback is likely to pose a greater problem for children than for adults due to growth of the ear canal and the close proximity of the hearing-aid microphone to the potential sources of acoustic leakage.

Fortunately, there are multiple cues to the perception of /s/. For example, the production of /s/ is often visible on the lips. In addition, cues may be available in the noise energy at lower frequencies, such as in the transition from fricative noise to the vowel (Whalen, 1981; Nittrouer and Miller, 2000; Jongman *et al.*, 2000). Zeng and Turner (1990), however, reported that adults with hearing loss do not appear to use the vocalic transition, but rather rely on fricative noise for perception of /s/. Interestingly, Nittrouer, Crowther, and Miller (1998) reported that young NH children tend to rely more on the vocalic transition than the fricative noise. Un-

fortunately, similar studies have not been conducted in young HI children.

In addition to acoustic properties, linguistic cues also can be used to indicate the presence of /s/ for listeners with normal language skills (e.g., "Give me a book" versus "Give me some books"). For NH children, it is likely that the development of these linguistic rules is contingent upon repeated exposure to multiple cues in a variety of contexts. It is not clear how well young HI children, who are still in the process of developing language, will be able to take advantage of linguistic cues when the audibility of /s/ is compromised.

It is important to emphasize that the focus of this study was HI children's perception of /s/ in quiet. As such, it is not possible to comment on the effects of high-frequency audibility on other phonemes or to rule out that an extended bandwidth may actually degrade performance for other speech sounds. Although studies using a wide range of speech sounds have been conducted with adults, additional studies are needed to address this issue for children. The current study represents a "worst case" scenario for the perception of /s/, because vocalic transitions and linguistic cues were not available to the listeners. Developmental studies using words and sentences are needed to refine our understanding of the importance of high-frequency audibility to the perception of /s/ and the formation of linguistic rules involving this phoneme. The current results also cannot be generalized to more difficult listening conditions, such as those in which noise and/or reverberation are present.

Since the spectra of talkers in the current study are consistent with earlier reports (Stevens, 1960; Heinz and Stevens, 1961; McGowan and Nittrouer, 1988; Nittrouer, Studdert-Kennedy, and McGowan, 1989; Boothroyd and Medwetsky, 1992; Boothroyd, Erickson, and Medwetsky, 1994; Jongman, Wayland, and Wong, 2000), these results suggest that, when fitting hearing aids to young children, audible energy through 5 kHz is needed to maximize perception of /s/ produced by a male talker and that a 9-kHz upper limit is needed for /s/ produced by a female. From a clinical perspective, it is important to distinguish between cases where performance *cannot be improved* by high-frequency amplification and cases where performance is actually *degraded*. In this study little or no evidence of degradation in the perception of /s/ was observed with increasing bandwidth. Previous studies with adults have produced mixed results with respect to this issue and, in all studies, the negative consequences of high-frequency amplification were evident in only some listeners. As such, when fitting hearing aids to young children, it would seem reasonable to provide as much of the prescribed high-frequency gain as possible. Exceptions would be those cases where it can be demonstrated that no usable hearing exists in the high-frequency region. In steeply sloping hearing losses, this can be determined by obtaining high-frequency thresholds in the presence of a low-pass masker (primarily to eliminate responses to amplifier noise). In addition, Moore *et al.* (2000) have developed a masking technique to identify "dead regions" within the cochlea (defined as areas where there is thought to be a complete loss of inner hair cells). If no usable hearing is present,

then provision of amplification in that frequency region would be unwarranted. In all other instances, however, the potential benefit of high-frequency amplification should be determined on an individual basis.

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