CHAPTER THIRTEEN

The Importance of High-Frequency Amplification for Young Children

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Introduction

In recent years, the utility of providing high-frequency amplification to some hearing-impaired individuals has been questioned. Specifically, in some cases, the provision of gain in the high frequencies may fail to improve speech perception or even result in a decrease in performance (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 high-frequency amplification cannot improve speech perception, then attempts to provide gain in this frequency region may not be necessary or desirable under certain circumstances.

Although the studies cited above were conducted only with adults, these findings often have been generalized to include the provision of amplification to infants and young children. The goal of this paper is to review the relevant studies in terms of their applicability to children and to present recent data from two studies conducted with hearing-impaired children.

Previous Studies

In general, previous studies appear to support the view that high-frequency amplification may not always be beneficial. It is important to point out that in all of these studies considerable inter-subject variability exists. That is, some subjects appear to be able to use high-frequency information, some show no benefit, and others show a decrease in performance. There also is disagreement regarding the degree and/or configuration of hearing loss that results in limited benefit from high-frequency amplification. Hogan and Turner (1998) concluded that the benefit of providing additional high-frequency audibility was negligible or negative when the degree of hearing loss at and above 4 kHz exceeded 55 dB HL. In the Ching et al. (1998) study, however, more than half of their subjects with 4 kHz thresholds between 55 and 80 dB HL benefited from audible energy in the high-frequency region. For this reason, they concluded that the total removal of high-frequency amplification should be limited to people whose high-frequency thresholds exceed 80 dB HL. Skinner (1980) assessed the recognition of monosyllabic words in 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-intensity speech. These differences across studies and the large inter-subject variability within studies suggest that degree and/or configuration of hearing loss alone cannot be used to separate individuals who are likely to benefit from high-frequency amplification from those who are not.

In addition, the methodology used in some studies may limit the interpretation of results. In a study by Murray and Byrne (1986), continuous discourse was low-pass filtered and adults with normal hearing and steeply-sloping hearing losses were asked to judge both intelligibility and pleasantness. The normal-hearing subjects preferred the widest bandwidth, but three of the five hearing-impaired subjects preferred the 2.5- or 3.5-kHz bandwidth over the

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widest bandwidth. However, these results may not be directly applicable to children because "judged" intelligibility does not necessarily correlate with objective measures of speech recognition.

The test stimuli used in a particular study also may influence the interpretation of results. For example, in the Hogan and Turner (1998) and Turner and Cummings (1999) studies, the set of nonsense syllables used contained a relatively small number of items comprised of high-frequency acoustic energy. One would not expect low-pass filtering to influence performance for test items that can be perceived from mid- and low-frequency cues (e.g., /b,d,g,l,m,n,r,dʒ/). When a large number of test items with differing acoustic characteristics are used as stimuli, performance differences for a subset of acoustically similar test items may not be reflected in the overall scores. Unfortunately, it is not possible to determine if this might have been the case in these studies because an error analysis was not reported. In a similar study by Sullivan, Allsman, Nielsen and Mobley (1992), however, an error analysis revealed that an increase in signal bandwidth resulted in improvements of 30–45% for the phonemes /s, ʃ, ʒ, z/.

Another stimulus issue is the linguistic complexity of test items. In the studies by Ching et al. (1998) and Ching, Dillon, Katsch and Byrne (2001), sentences were used as the test materials. When contextual information is available, degradation due to noise, filtering, or a variety of other manipulations is not likely to be as detrimental as when non-meaningful materials are used. Since infants and young children in the process of developing language are not likely to have the world knowledge or linguistic competence of adults with acquired hearing losses, they are not as able to "fill in the blanks" when a signal is degraded in some way. As such, it may be inappropriate to generalize the results of studies such as this to pre-lingually hearing-impaired children.

Effects of Hearing Loss on Speech and Language Development

While the effects of severe-to-profound hearing loss have been studied extensively, relatively little is known about the effects of mild-to-moderate hearing loss on speech and language development in young children. Davis, Elfenbein, Schum and Bentler (1986) investigated the language skills of 40 children with mild-to-moderate hearing loss. Results revealed significant delays in vocabulary development, verbal abilities, and reasoning skills. Children with mild-to-moderate sensorineural hearing loss also have been found to demonstrate increased errors in noun and verb morphology (Elfenbein, Hardin-Jones and Davis 1994; Norbury, Bishop and Briscoe 2001). Specifically, these children had difficulty perceiving the final /s/ or /z/ that denote plurality, possessiveness, and verb tense (e.g., cat vs. cats, Bob vs. Bob's, keep vs. keeps). Interestingly, Teele, Klein, Chase, Menyuk and Rosner (1990) as well as Petinou, Schwartz, Gravel and Raphael (2001) found similar delays in the morphological development of children with a history of recurrent otitis media. It has been suggested that the observed delays in morphological development may be related to a reduction in audibility of the fricative noise and/or the vocalic transition due to the presence of hearing loss.

When hearing loss is acquired later in life, as is often the case with adults, there may be sufficient redundancy in speech cues to overcome this loss of audibility. When the hearing loss is congenital or acquired early in life, however, the reduction in audibility may delay the development of language and/or the acquisition of language rules. Children learn the rules of language through repeated exposure in a variety of contexts. For example, after repeated usage of phrases such as, "Give me *some* jelly bean*s*" or "Take *some* apple*s* to your teacher", children learn to associate the word *some* with the fricative noise, /s/ in the following word. This paired association eventually leads to the understanding of a language rule (e.g., *some* means there will be more than one). If the fricative noise is inaudible or inconsistently audible, the language concept may be delayed.

Bandwidth Effects for Children with Sensorineural Hearing Loss

In a recent study, Kortekaas and Stelmachowicz (2000) investigated the effects of low-pass filtering on the perception of /s/ in normal-hearing adults and 5–10 year-old-children. Results revealed that, in noise, children required a wider signal bandwidth than adults in order to perceive /s/ correctly. These developmental differences for normal-hearing children raise the issue of whether restriction of the stimulus bandwidth for children with hearing loss may have a negative impact on speech and language development.

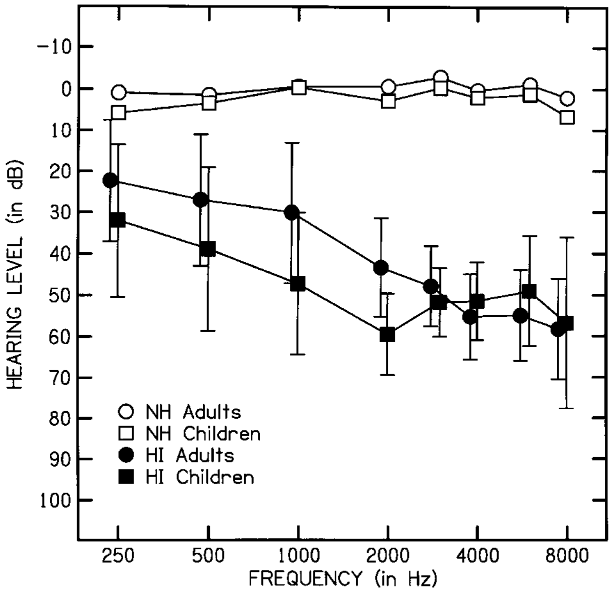

Figure 1. Mean audiometric thresholds for the 4 groups of subjects tested in the Stelmachowicz et al. (2001) study. Error bars are shown only for the hearing-impaired listeners and represent ±1 standard deviation. (Reproduced with permission)

The paradigms used by Hogan and Turner (1998) and Turner and Cummings (1999) are probably the most straightforward way to assess the effects of stimulus bandwidth on perception. Thus, this general approach was used to evaluate the effects of high-frequency audibility on the perception of /s/ in normal-hearing and hearing-impaired adults and children (Stelmachowicz, Pittman, Hoover and Lewis 2001). Four groups of 20 subjects were included in order to assess the effects of both hearing loss and age. Figure 1 shows the mean audiograms for these four groups. The adults ranged from 19–43 years of age and the children ranged from 5–8 years of age. All of the children were prelingually hearing impaired and the adults had hearing losses that were acquired later in life. Although the focus of this study was the perception of /s/, the phonemes /f/ and /θ/ were included because pilot studies revealed that low-pass filtering typically resulted in /s/ being perceived as one of these two phonemes. Each phoneme was paired with the vowel /i/ to produce both a consonant-vowel and vowel-consonant stimuli. Test stimuli were spoken by three talkers: an adult male, an adult female, and a 6-year old child. The spectral characteristics of /s/ varied across the talkers with peak energy at 8–9 kHz for the female, 4–5 kHz for the male, and 6 kHz for the child. Stimuli were low-pass filtered at 2, 3, 4, 5, 6, 8, and 9 kHz and presented randomly through earphones with an extended high-frequency response. The subject's task was to select the appropriate response on a computer screen.

Figure 2 shows mean performance as a function of filter frequency for the male, female, and child

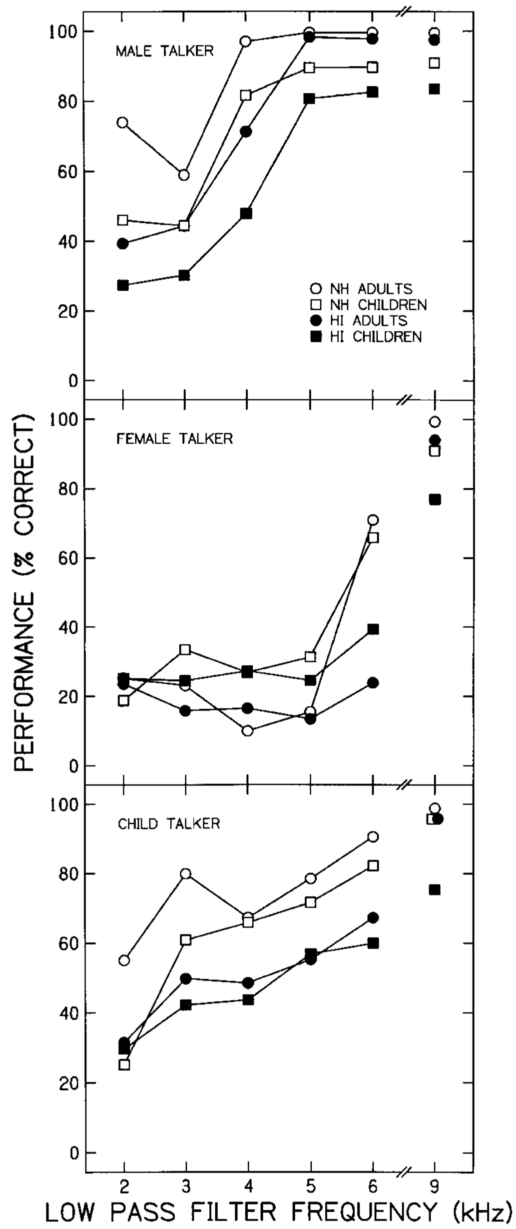

Figure 2. Mean performance as a function of low-pass filter frequency for the three talkers in the Stelmachowicz et al. (2001) study. Parameter in each panel is the subject group. (Reproduced with permission)

talkers. The parameter in each panel is group. For the male talker, the normal-hearing adults reached maximum performance at a bandwidth of 4 kHz. In contrast, mean values for the other 3 groups did not reach maximum performance until the bandwidth was extended to 5 kHz. Furthermore, maximum performance for the two groups of children was lower than their adult counterparts, consistent with previous studies that have compared the performance of adults and children on a variety of tasks (Neuman and Hochberg 1983; Wightman, Allen, Dolan, Kistler and Jamieson 1989; Veloso, Hall and Grose 1990; Nozza, Rossman and Bond, 1991). When listening to the female talker, mean performance for the normal hearing subjects was near chance until a bandwidth of 5 kHz. Performance at a 6 kHz bandwidth increased to approximately 70% but continued to improve as more high-frequency energy was provided. For the two groups of hearing-impaired subjects, performance did not improve much above a chance level until 9 kHz. On average, maximum performance for the hearing-impaired children was only 77%. Performance changes with stimulus bandwidth were more gradual for the child talker. The two groups of hearing-impaired subjects had mean scores that were approximately 20% poorer than their normal-hearing counterparts for bandwidths from 3 to 8 kHz. Interestingly, mean performance for the hearing-impaired adults increased to almost 100% at a bandwidth of 9 kHz, while the mean performance for the hearing-impaired children was similar to their performance for the female talker (75%).

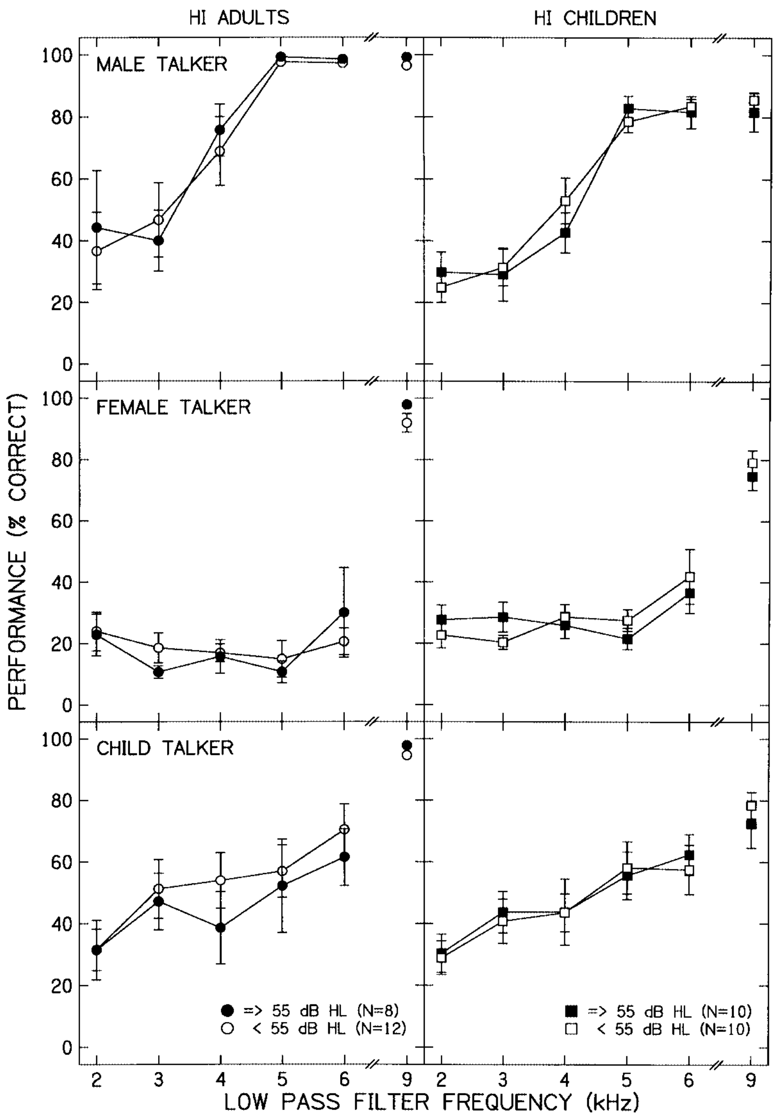

Figure 3. Data from the hearing-impaired subjects in figure 2 have been regrouped to show the effects of degree of hearing loss (< or ≥ 55 dB HL at 4 kHz) (Stelmachowicz et al. 2001). The left and right columns show the adult and child data, respectively. (Reproduced with permission)

As stated previously, Hogan and Turner (1998) concluded that subjects with hearing losses greater than 55 dB HL at 4 kHz may not benefit from an increase in audibility in the high frequencies. To determine if the data from the current study showed a similar pattern, two different analyses were performed. The results of the first analysis are shown in figure 3. The left and right columns show data from the hearing-impaired adults and children, respectively. The results in figure 2 have been regrouped to show subjects with hearing losses < 55 dB HL (open symbols) or ≥55 dB HL (filled symbols) at 4 kHz. No obvious differences in the mean performance of these two groups are apparent. To investigate this in more detail, however, the 120 individual performance-intensity functions (3 talkers x 20 listeners) for the two groups of hearing-impaired listeners were inspected. None of the performance intensity functions for the hearing-impaired adults revealed evidence of nonmonotonicity. However, at the widest bandwidth, one of the 20 hearing-impaired children showed a statistically significant decrease in performance for the female talker and another child showed a decrease in performance for both the female and child talkers. In the Ching et al. (1998) study, approximately 20% of their listeners with hearing losses similar to those in the Stelmachowicz et al. (2001) study (thresholds between 55 and 70 dB HL at 4 kHz) showed degradation in sentence perception. Although it is more difficult to estimate the performance degradation for listeners with hearing losses > 55 dB HL from the Hogan and Turner (1998) study, but it appears that it would be at least 60–70%. The observed differences between these studies and the Stelmachowicz et al. (2001) study may be due to the fact that the listeners in the Hogan and Turner and Ching et al. studies had much poorer high-frequency thresholds.

The results of the Stelmachowicz et al. (2001) study suggest that both age and hearing loss affect the perception of /s/ under filtered conditions and that young hearing-impaired listeners are at the greatest disadvantage. Furthermore, the performance differences observed for the three talkers may have important implications for speech and language development in infants and young hearing-impaired children. Specifically, mean performance for the female and child talkers continued to improve as the bandwidth increased up to 9 kHz. Since hearing aids generally do not provide large amounts of gain above 5 kHz, it is likely that the peak energy of a female /s/, in particular, may not always be audible to hearing-aid users. Since infants and toddlers tend to spend most of their early years with female caregivers and other children, their early auditory experiences with /s/ may be inconsistent. They may have no difficulty hearing /s/ when spoken by males, but may only occasionally hear a female or child /s/. These inconsistencies could serve to impair or delay the formation of linguistic rules (e.g., plurality, possessiveness, tense) related to this very important speech sound.

Effects of Amplification on Fricative Audibility

The results of the above study led the investigators to question how well hearing-impaired children would be able to perceive the phoneme /s/ after processing by a hearing aid (Stelmachowicz, Pittman, Hoover and Lewis in review). In this study they were particularly interested in how well these children could perceive the bound morpheme /s/ or /z/ (e.g., cat vs. cat*s*, bug vs. bug*s*). Although the addition of –s and –z to denote plurality is evident in the speech samples of normal-hearing children by 3 years of age, similar methodology could not be used with young hearing-impaired children because it would be difficult to separate perception from production errors. Thus, a picture-based test of morpheme perception was devised. Figure 4 illustrates one example from this test which consisted of 20 easily identified nouns in either plural or singular form. Test items were spoken by both a male and a female talker (e.g., "Show me babies"). Stimuli were presented in the sound field at

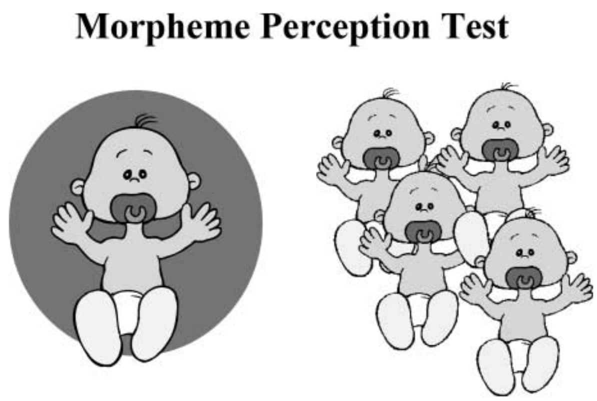

Figure 4. Example of a test item from the Morpheme Perception Test (Stelmachowicz et al. in review). The child would hear either "Show me baby" or "Show me babies".

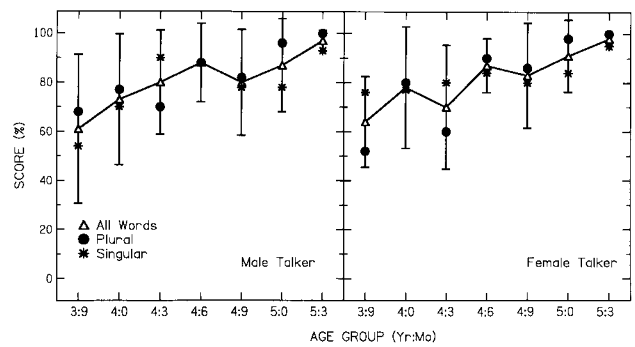

Figure 5. Percent correct for all words (open triangles) as a function of age group for the 36 normal-hearing children. Error bars show ±1 standard deviation from the mean for the overall scores. Filled circles and asterisks show mean results for the plural and singular test items, respectively. The left and right panels show data for the male and female talkers, respectively.

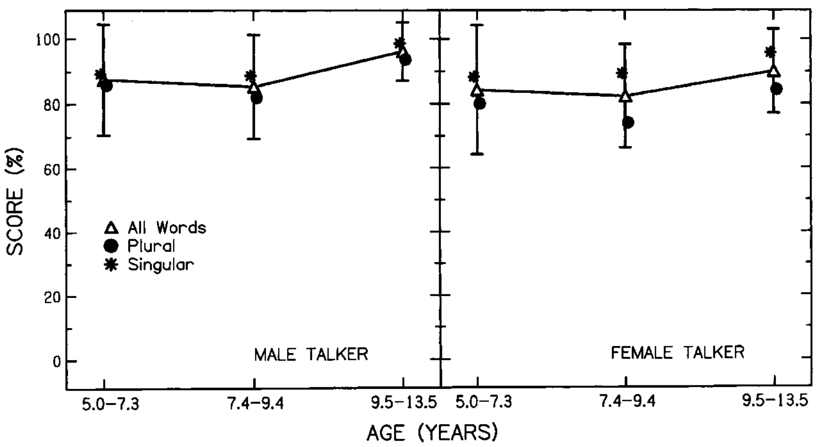

Figure 6. Percent correct as a function of age group for the 40 hearing-impaired children. Filled circles and asterisks show mean results for the plural and singular test items, respectively.

50 dB HL and the child's task was to point to the correct item(s). To ensure that normal-hearing children could perform this task, 36 children between the ages of 3 and 5 years were evaluated. Figure 5 shows the performance for both talkers as a function of age group. The open triangles represent the individual data ∇1 standard deviation (SD). The filled circles and asterisks show the mean results for the plural and singular test items, respectively. Although there is considerable variability across subjects, by approximately 5 years of age performance for most children was close to 100%, regardless of talker gender.

Accordingly, the youngest hearing-impaired children enrolled in this study were 5 years of age. For this group only, 7 irregular test items (e.g., foot vs. feet) were added to determine if these children had the concept of plurality even if they could not perceive /s/ or /z/. Forty children (5–13 years) with varying degrees and configurations of hearing loss were evaluated. All children were aided binaurally and wore their personal hearing aids at their normal use settings. Probe-tube microphone measures were used to quantify audibility of the fricative noise for each child. All other procedures were similar to those used with the normal-hearing children. Results for these 40 hearing-impaired children are shown in figure 6, following the convention used in figure 5. Here, the 40 subjects have been grouped into three age categories: 5.0–7.3 years, 7.4–9.4 years, and 9.5–13.5 years. While the mean overall scores are above 80% for both talkers, the errors bars suggest considerable variability compared to that observed for the oldest normal-hearing children tested (5 years). Inspection of the individual data revealed that some very young children demonstrated 100% performance, while some children as old as 11–12 years had relatively poor performance. In contrast to the data from the normal-hearing children, the hearing-impaired children had more difficulty with the plural test items than with the singular items. To determine what factors might be responsible for the variability in the data from the hearing-impaired children, a factor analysis was conducted. Factors included: age at test, age of amplification, performance on the irregular test items, hearing level, and aided fricative audibility (sensation level). Results revealed that 79% of the variance could be accounted for by sensation level and hearing level in the high frequencies. Interestingly, the frequency range of importance was 2–4 kHz for the male talker and 2–8 kHz for the female talker. These results are consistent with the acoustic spectra for the female and male /s/ and /z/.

It is important to note that there are multiple cues to perception. It is possible that the hearing-impaired children in this study may have used secondary acoustic cues, such as formant transitions to perceive /s/ or /z/. To explore this further, the plural errors for both talkers were analyzed in terms of the strength of the transition from the preceding vowel or consonant to the final /s/ or /z/. This transition is generally lower in frequency than the fricative noise and may provide a more audible signal than the fricative for many of the hearing-impaired listeners. Using spectrograms of the test stimuli, these transitions were rated by three of the investigators as either strong, moderate, or no transition. Figure 7 shows the error rate (in percent) for each plural test item for the male (left panel) and female (right panel) talkers. For the male talker, the most errors occurred for test items judged to have no transition. In contrast, no clear pattern emerges for the female talker. These results suggest that the transitions produced by the male talker were more informative to these children than those of the female talker. It is also possible that this disparity might be related to the acoustic characteristics of the male and female /s/ and /z/. For the male talker, where the fricative noise was clearly

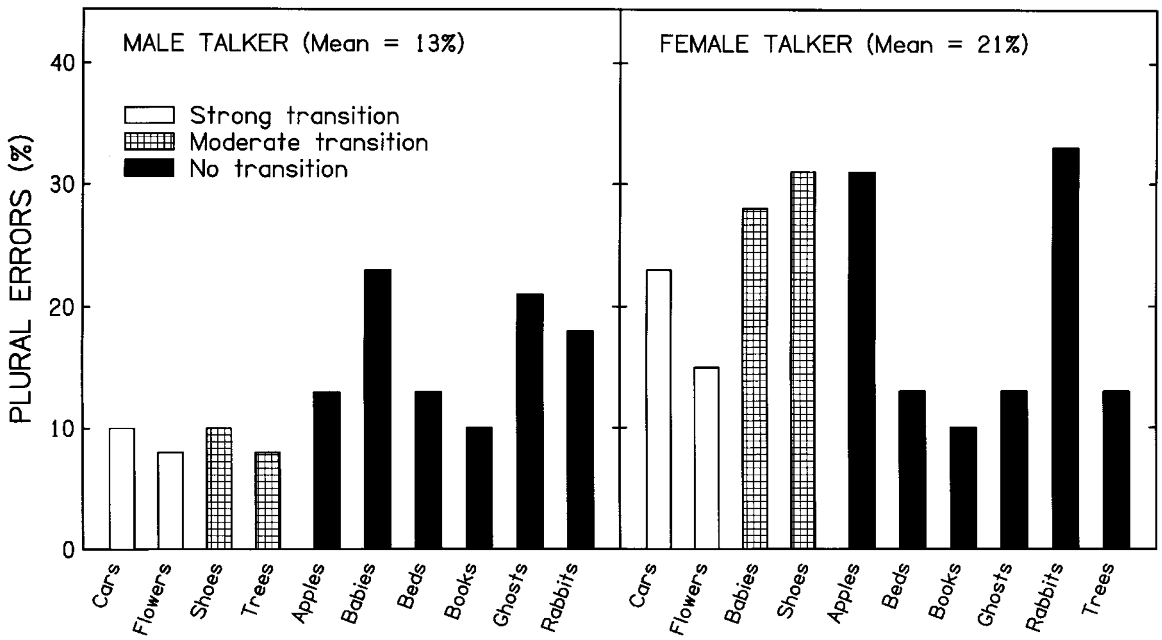

Figure 7. Error rate (in percent) for the plural words only as a function of test item. The parameter in each panel is the strength of the transition into the fricative. The left and right panels show data for the male and female talkers, respectively.

audible, addition of a transition seemed to improve performance. In the case of the female talker, the absence of audible fricative noise could not be overcome by the presence of a transition. It is possible that the reduced audibility for female fricatives resulted in an inconsistent exposure to these speech sounds. That is, for a male talker, both the transition and the fricative noise may be audible most of the time. For a female talker, however, the transition is more likely to be audible but audibility of the fricative noise may be more variable. These inconsistencies may make it difficult for the child to learn to associate the presence of the transition with the fricative noise. Interestingly, Zeng and Turner (1990) found that adults with sensorineural hearing loss were less able to use transition cues to identify voiceless fricatives than were normal-hearing listeners, even when the transition was clearly audible. They attributed this finding to poorer than normal discrimination ability for the dynamic spectral cues involved in the transition. This factor, as well as an inability to form a clear association between the two types of cues, may explain the results observed for the hearing-impaired children. These results should be interpreted with caution, as this particular study was not specifically designed to explore the use of transition information.

How Important is High-Frequency Amplification for Infants and Young Children?

The answer to this question is very complex and there are still many other unanswered questions that require additional studies. As discussed in the Introduction, it is unlikely that the available adult data can be used to predict performance in young children. Unfortunately, only a few studies have been conducted with hearing-impaired children and no studies with infants have been reported. In addition, the children's studies cited in this paper have focused solely on the perception of fricatives, so one could argue that these results may not apply to speech perception in general. If one believes, however, that high-frequency speech sounds are important to speech and language development, these fricative perception studies may be meaningful. It is also noteworthy that young hearing-impaired children have the most difficulty perceiving fricatives spoken by females and other children. This finding may have important implications in the early years.

Recall that a number of studies conducted with adults showed *degradation* in performance with increasing bandwidth. This finding may be due to the poorer than normal frequency or temporal resolution often found in listeners with sensorineural hearing loss. Recently, Moore, Huss, Vickers, Glasberg and Alcantara (2000), showed that "dead regions" may exist within the cochlea and that these can be predicted from either psychophysical tuning curves or a more simplified masking paradigm. They suggest that these are regions in which there is a complete loss of inner hair cell function. These findings have important implications for hearing-aid fittings because individuals with high-frequency dead regions would not be expected to benefit from amplification in the dead region. In a follow-up study, they demonstrate that there may be some benefit in amplifying frequencies that are 50–100% above the estimated edge of the dead region (Vickers, Moore and Baer 2001). They emphasize that listeners with severe hearing loss but no evidence of dead regions usually appear to benefit from high-frequency amplification. For older children and adults, the use of this masking paradigm would appear to be a very useful clinical tool to determine when to provide high-frequency amplification. It is possible that masked evoked potential measures could be used to achieve the same goal, but no studies have yet been conducted.

From a clinical perspective, it is important to note that there is a fundamental difference between a *decrease* in performance with increasing bandwidth and a failure to observe an *improvement* in performance. If it can be demonstrated that an individual child performs *more poorly* with an extended high-frequency response, then it would make sense to restrict the bandwidth. In most cases involving young children, however, it will be difficult to make this determination. Most of the studies that have addressed the issue of stimulus bandwidth have been conducted in quiet with a limited set of experimental conditions. For some children, it is possible that the provision of high-frequency amplification may be of little or no benefit in quiet but may be helpful in noisy or reverberant environments. Until further studies can be conducted, it is probably wise not to restrict the stimulus bandwidth unless it can be proven that performance degradation occurs or that dead regions exist in the high frequencies.

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